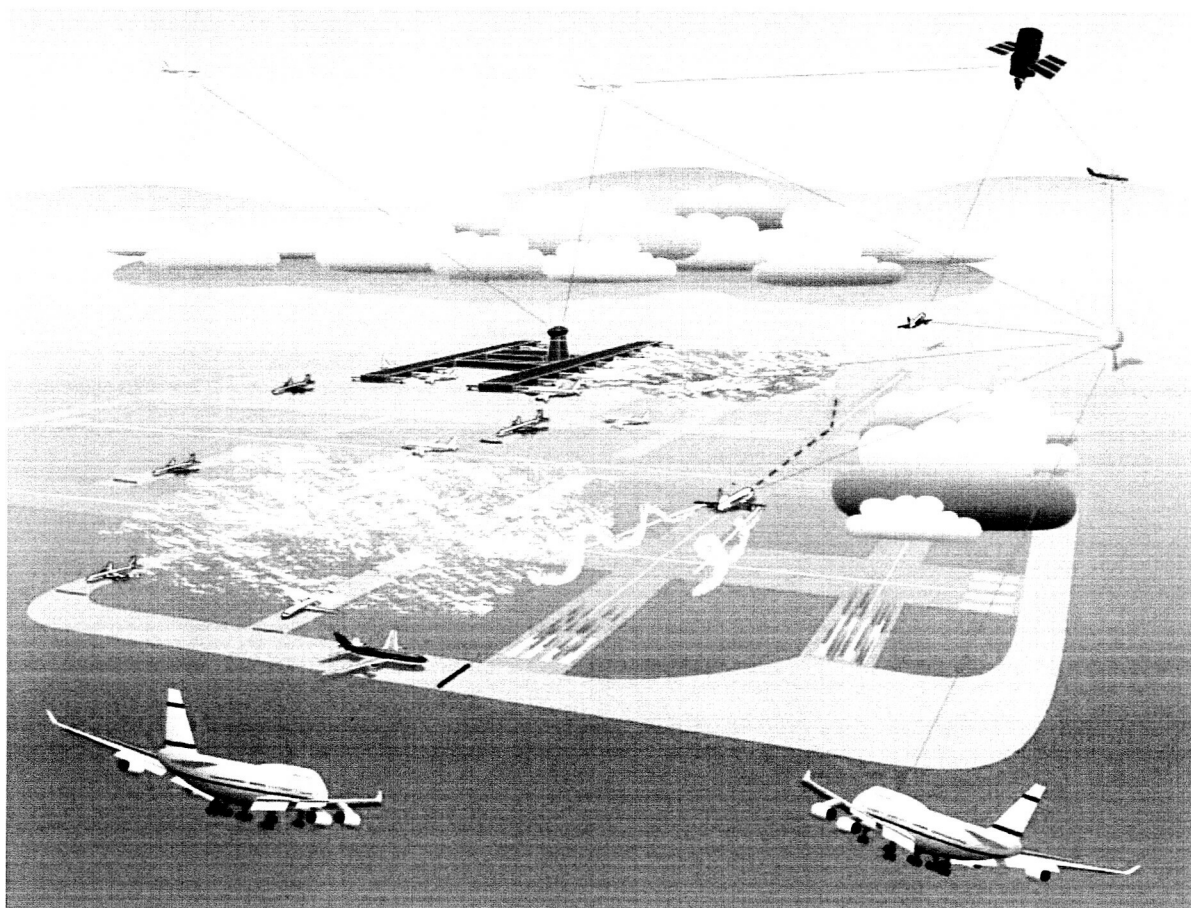




**Aviation System Capacity Program  
Terminal Area Productivity Project  
Ground and Airborne Technologies**

*Demo J. Giulianetti*



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**Aviation Systems Capacity Program  
Terminal Area Productivity Project  
Ground and Airborne Technologies**

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## Foreword

This report is a timely summarization of all the work conducted in support of the Terminal Area Productivity (TAP) project. With the explosive growth in air travel for both commercial air passengers and air cargo following the Airline Deregulation Act of 1978, the capacity of the National Airspace System is becoming strained. Thus, with the projected increases in world air traffic, our government sees a need to address the growing issue of flight delays caused by insufficient National Airspace System capacity.

The main components of the National Airspace System are the navigation, communication, surveillance, weather, and air traffic control infrastructure. These components provide the framework for managing air traffic around the country. As air traffic continues to grow, in a system which is unable to handle the growth, the National Airspace System infrastructure becomes strained to such an extent that delays and system gridlock become more frequent occurrences. TAP addressed the terminal-area component of the infrastructure system.

Airline commercial carriers have also cited insufficient National Airspace System capacity as a principal factor in gridlock and time delays prior to or during a flight and in excessive operating costs for personnel and fuel, all of which are reflected as increased ticket prices to the flying public. As with any system that becomes over subscribed, the capacity of the system reaches a limit where efficient and safe operations are no longer possible. In addition, air transportation also enables fast, global shipping and is critical to commerce. Therefore it is most important that a fully effective National Airspace System be maintained in the interest of efficient operations.

Several of the research technologies addressed in the TAP effort require additional development in order to mature the technology readiness before its transition to industry or the FAA. At the writing of this report, NASA is formulating a new project called Aviation System Technology Advanced Research (AvSTAR) which may fund these additional developments.

Frank Aguilera  
Deputy Director  
Aviation System Capacity Program

TAP Project Manager  
In the year 2000 and on to its successful completion.





## Abbreviations

AASI	Air-Air Traffic Control Systems Integration	IFR	Instrument Flight Rules
AATT	Advanced Air Transportation Technologies	ILS	Instrument Landing System
ACFS	Advanced Concepts Flight Simulation	IMC	Instrument Meteorological Conditions
aFAST	active FAST	LaRC	Langley Research Center
ADS-B	Automatic Dependent Surveillance-Broadcast	LNAV	Lateral Navigation
AILS	Airborne Information for Lateral Spacing	LVLASO	Low-Visibility Landing And Surface Operations
ARTCC	Air Route Traffic Control Center	MIT	miles-in-trail
ASC	Aviation System Capacity	MSP	Minneapolis-St. Paul International Airport
ASDE	Airport Surface Detection Equipment	NAS	National Airspace System
ATC	Air Traffic Control	pFAST	passive FAST
ATIDS	Airport Target Identification System	PRM	Precision Runway Monitor
ATM	Air Traffic Management	QAT	Quiet Aircraft Technology
AVOSS	Aircraft Vortex Spacing System	RFD	Research Flight Deck
AvSTAR	Aviation System Technology Advanced Research	RIRP	Runway Incursion Reduction Program
CNS	Communication, Navigation, and Surveillance	ROT	Runway Occupancy Time
CTAS	Center TRACON Automation System	ROTO	Roll-Out and Turn-Off
DA	Descent Advisor	RSO	Reduced Separation Operations
DAG	Distributed Air Ground	RVR	Runway Visual Range
DFW	Dallas-Fort Worth International Airport	SEATAC	Seattle-Tacoma
DGPS	Differential Global Positioning System	SHCT	Short Haul Civil Tilt Rotor
DROM	Dynamic Runway Occupancy Measurement	SGS	Surface Guidance System
EFIS	Electronic Flight Instrument System	SMA	Surface Movement Advisor
EMM	Electronic Moving Map	TAF	Terminal Area Forecast
FAA	Federal Aviation Administration	TAP	Terminal Area Productivity
FFP1	Free Flight Phase 1	TCAS	Traffic Alert and Collision Avoidance System
FAST	Final Approach Spacing Tool	TMA	Traffic Management Advisor
FMS	Flight Management Systems	TMA-SC	Traffic Management Advisory-Single Center
FPL	Full Performance Level	TMC	Traffic Management Coordinator
GPS	Global Positioning System	T-NASA	Taxiway Navigation and Situation Awareness
HDD	Head Down Display	TRACON	Terminal Radar Approach Control
HUD	Head Up Display	TSRV	Traffic Systems Research Vehicle
ICAO	International Civil Aviation Organization	VMC	Visual Meteorological Conditions
IDS	Integrated Display System	VNAV	Vertical Navigation

## Overview

Ground and airborne technologies were developed in the Terminal Area Productivity (TAP) project for increasing throughput at major airports by safely maintaining good-weather operating capacity during bad weather. Methods were demonstrated for accurately predicting vortices to prevent wake-turbulence encounters and to reduce in-trail separation requirements for aircraft approaching the same runway for landing. Technology was demonstrated that safely enabled independent simultaneous approaches in poor weather conditions to parallel runways spaced less than 3,400 ft apart. Guidance, control, and situation-awareness systems were developed to reduce congestion in airport surface operations resulting from the increased throughput, particularly during night and instrument meteorological conditions (IMC). These systems decreased runway occupancy time by safely and smoothly decelerating the aircraft, increasing taxi speed, and safely steering the aircraft off the runway. Simulations were performed in which optimal trajectories were determined by air traffic control (ATC) and communicated to flight crews by means of Center TRACON Automation System/Flight Management System (CTAS/FMS) automation to reduce flight delays, increase throughput, and ensure flight safety.

## Introduction

The Aviation System Capacity (ASC) program was established in 1996 in response to the challenges associated with increasing air-traffic capacity at major U.S. airports and with modernization of the National Airspace System (NAS). The ASC program, which is managed at Ames Research Center, has the goal of enabling large increases in the traffic capacity of major U.S. airports by improving the NAS. The objectives of the program were to accommodate projected growth in air traffic while maintaining and enhancing system safety, reducing delays, and providing airspace-system users with increased flexibility in the use of airports, airspace, and aircraft, and to maintain pace with a continuously evolving technology. To accomplish these

objectives, the ASC program integrated activities in three major projects: the Terminal Area Productivity (TAP) project, the Advanced Air Transportation Technologies (AATT) project, and the Short Haul Civil Tilt Rotor (SHCT) project. The TAP project, which will be completed in 2000 and which is the subject of this document, was initially started in 1994 as its own project under the Advanced Subsonic Technology program and was led by NASA Langley Research Center.

## Terminal Area Productivity Project

Most delays are caused by poor weather and are attributable to nonvisual or instrument conditions in the terminal airspace and to low-visibility conditions on the airport surface. The Federal Aviation Administration (FAA) reported that between 1990 and 1993 air carriers experienced delays of 15 min or more on 312,000 flights annually in the United States (ref. 1). Sixty-four percent of these delays were caused by poor weather. The costs associated with these delays in 1990 alone were estimated to be in excess of \$3 billion to airline operations and \$6 billion to passenger delays. To address this problem, NASA initiated the Terminal Area Productivity (TAP) project, which was initially under the Advanced Subsonic Technology program and later under the ASC program. The goal of the project was to reduce the number of delays and to increase the safety of terminal-area operations during low-visibility conditions to levels comparable to those of clear weather operations. Technology developed under the TAP project focuses on increasing terminal-area capacity in instrument meteorological conditions (IMC), reducing delays by reducing spacing requirements between aircraft on the approach, and by expediting ground operations. To accomplish this, four sub-elements under TAP were formed: the Reduced Separation Operations (RSO), the Low-Visibility Landing and Surface Operations (LVLASO), the Air Traffic Management (ATM), and the Aircraft-Air Traffic Control Systems Integration (AASI) elements. The objectives of these sub-elements were (1) to achieve a combined overall increase in current nonvisual operations for single runway throughputs of 12% to 15%, (2) to reduce lateral runway spacing to less

than 3,400 ft for independent operations on parallel runways, (3) to demonstrate equivalent instrument/clear-weather runway occupancy time, and (4) to meet FAA guidelines for safety.

To achieve these objectives, each of the four sub-elements was divided into task-oriented areas as shown in figure 1. RSO focused on developing ground-based and airborne technologies to reduce longitudinal and lateral spacing, including positional uncertainty in nonvisual conditions. ATM developed Center TRACON Automation System (CTAS) enhancements that include on-board automation and TAP technologies to reduce spacing and position uncertainty. LVLASO focused on developing sensor/display/guidance, navigation, and control technology to permit expeditious airport surface operations in CAT III conditions (300 ft runway visual range). The benefits analysis of implementing these technologies was estimated under AASI.

## Reduced Spacing Operations

Ground-based and airborne technologies having connections to ground-based components were developed in the NASA Langley-led RSO sub-element within the TAP project. RSO focuses on increasing airport terminal-area throughput by reducing in-trail and lateral spacing requirements in the approach and landing operations, both in visual meteorological conditions and during IMC. Ground-based technologies were developed for the purpose of predicting, in real time, the life cycle of wake turbulence in order to determine the minimum safe spacing between aircraft approaching a single runway. Concepts, procedures, and supporting technology that demonstrate safe reductions below the standard minimum lateral separation of 4,300 ft in visual conditions to 2,500 ft for independent instrument approaches on parallel runways were developed.

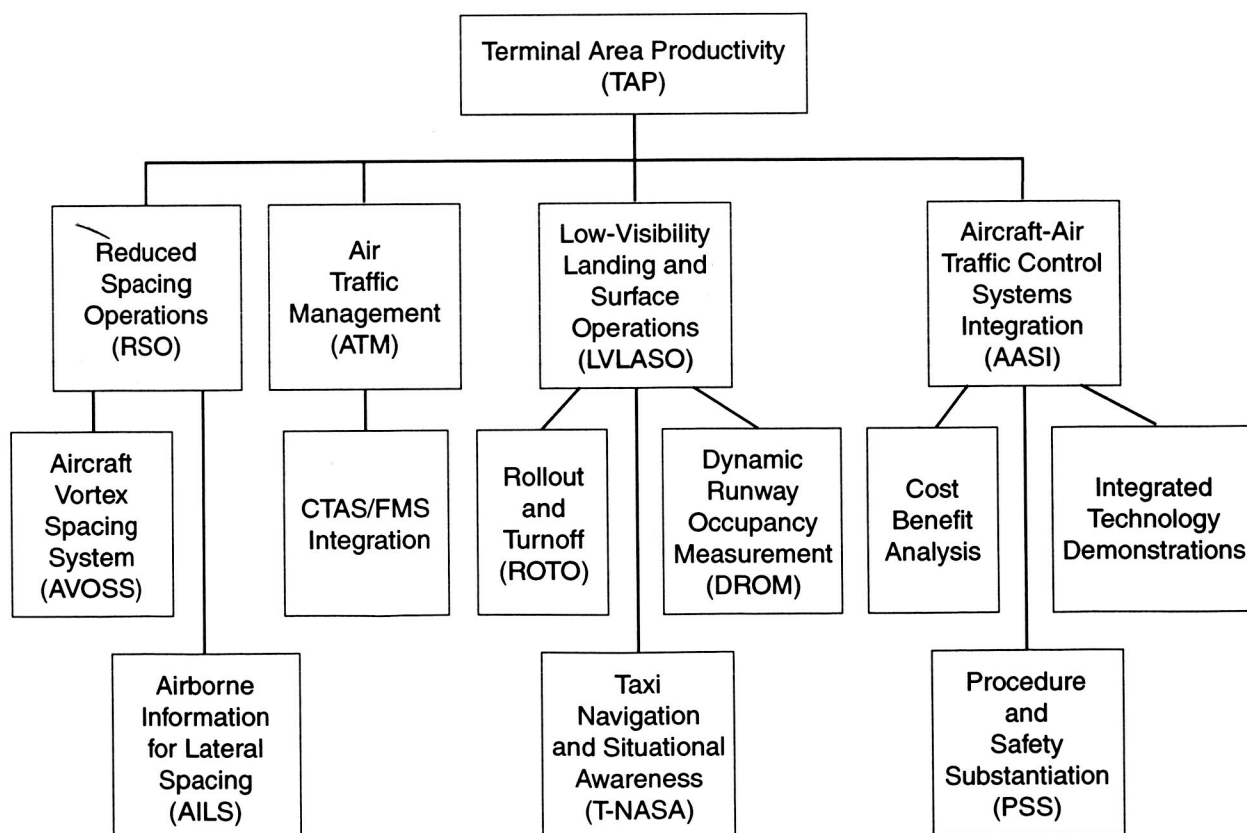


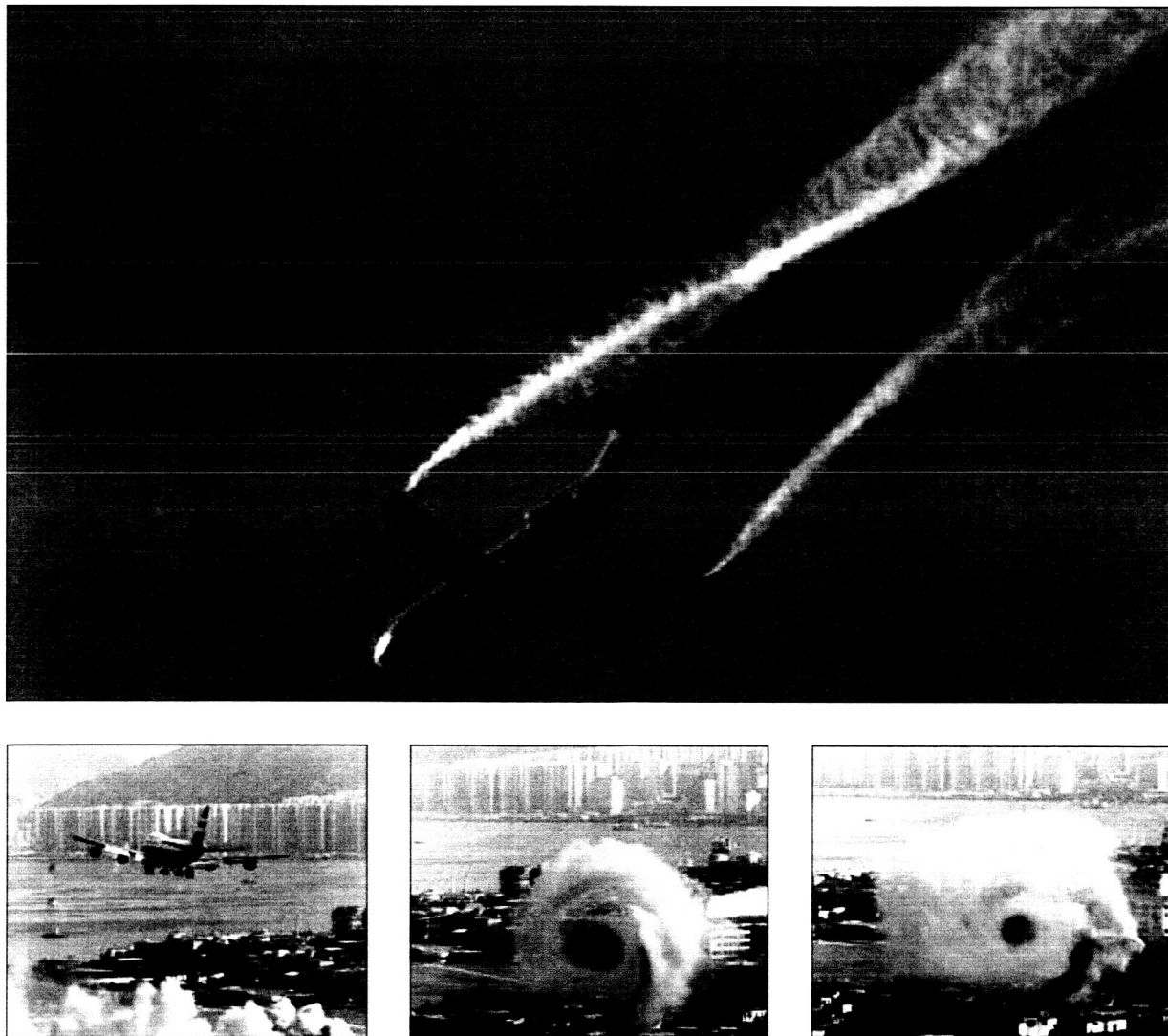
Figure 1. Sub-elements and associated technical work areas within the TAP project.

Technology and procedures were also developed which (1) reduce runway threshold and metering fix arrival-time errors, (2) reduce interruptions in descent caused by conflicts in user-preferred trajectories, and (3) maximize the issuance of user-preferred Air Traffic Control (ATC) clearances in order to improve fuel efficiency and increase airplane operator acceptance of CTAS automation.

### **Aircraft Vortex Spacing System**

A major factor limiting airport capacity in nonvisual (IMC) terminal operations is the in-trail

separation requirement for aircraft approaching the same runway for landing. This requirement is necessary to ensure that wake turbulence generated by the lead aircraft will have dissipated or moved out of the approach corridor so that the following aircraft will not encounter it. Vortices typical of a landing transport aircraft that create in-trail wake turbulence are shown in figure 2. The longitudinal separations between landing aircraft in nonvisual conditions are often greater than necessary because of wake-turbulence separation constraints used by ATC to account for uncertainties in the behavior of wake vortices (shown in fig. 3 as buffer zones).



*Figure 2. Wake vortices generated by a landing transport aircraft.*

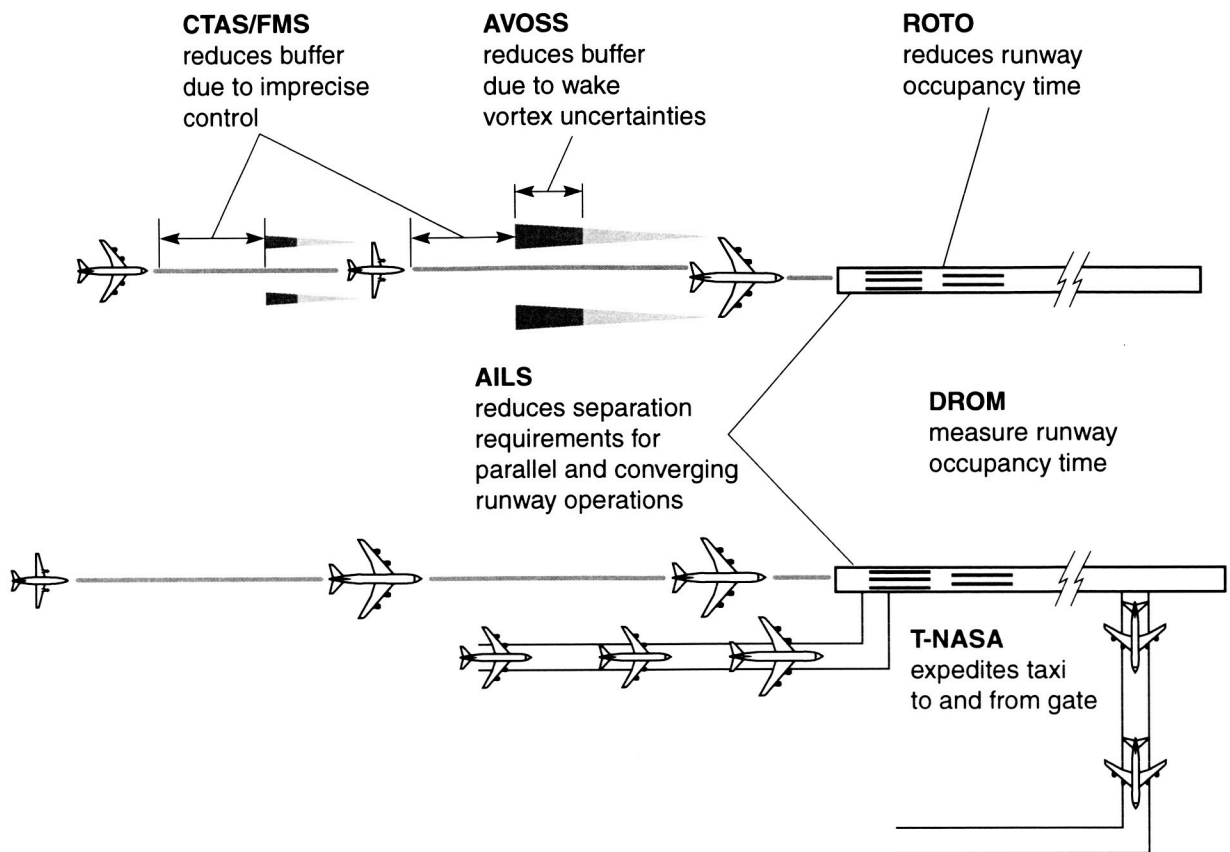


Figure 3. Overview of TAP technologies as applied to airport surface operations and to in-trail and lateral spacing between landing aircraft.

An activity under the RSO sub-element is a ground based Aircraft Vortex Spacing System (AVOSS). The goal of this activity is to improve terminal-area throughput by reducing the inefficient separation between aircraft caused by the effects of wake vortices. AVOSS provides a dynamic aircraft vortex-spacing prediction capability for use in either the Center Terminal Radar Approach Control (TRACON) Automation System (CTAS) or a manual ATC environment that uses current and future near-term weather conditions to determine when vortices from the lead aircraft have left the approach corridor. The separation necessary to prevent trailing aircraft encounters with vortices generated by the lead aircraft is calculated by integrating these weather conditions to model wake-vortex transport and decay and to provide real-time feedback of wake-vortex behavior from sensors. Within 200 ft of the runway elevation where the vortices cannot

sink out of the approach corridor, only vortex lateral motion and demises are considered in determining the safe spacing for larger aircraft. AVOSS verifies these predictions by sensing and tracking actual vortices from each aircraft; it increases the spacing should the prediction underestimate the residence time of the actual vortices in the approach path. The basic architecture of AVOSS has not changed (refs. 2-4) and is shown in figure 4.

AVOSS is time-dependent and focuses on the approach application providing separation criteria by aircraft category (small, large, and heavy) for a 30-min period based on measured vertical wind profiles, on an aircraft data base, and on an approach safety corridor (fig. 5). The wake predictor provides a time-history of the wake motion and decay that is passed to an algorithm that calculates and compares the wake trajectory to

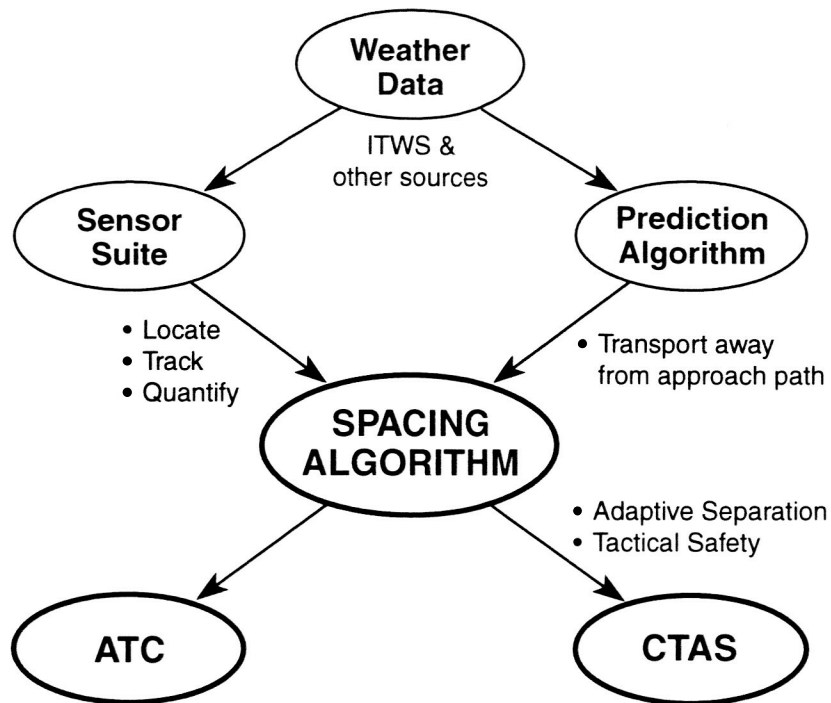


Figure 4. AVOSS System Architecture.

the safety corridor limits. This provides wake residence time values that describe the time required for the wake to exit the lateral or vertical corridor limit, or to decay below the demise value. The separation criteria are based on the time required for wakes from the leading aircraft to sink or drift out of the safety corridor. Once a wake has drifted beyond the lateral limits of the corridor or descended below the floor, it is no longer considered a potential hazard to following aircraft. Wake behavior is calculated at a set of windows in the approach corridor from the glide-slope intercept altitude to the runway threshold. Each window models the wake at a different location and altitude on the approach. Weather statistics at the altitude of the flightpath at each approach window were used to run the wake-vortex prediction algorithm. The number of windows used to model the wakes can be changed at run time to, for example, increase window density near the altitude of any unusual meteorological conditions. These calculations were repeated for each aircraft type at each window. The program also applied a minimum threshold spacing for considerations of runway occupancy

time. The output of AVOSS is aircraft spacing at the top of the approach safety corridor that meets wake-vortex safety requirements, as well as minimum threshold spacing for runway throughput considerations.

An initial field-test deployment and operation of AVOSS at the Dallas-Fort Worth International Airport (DFW) was conducted in 1997 with additional testing in 1998. These tests were highly successful from the perspective of establishing a facility for on-site and remote AVOSS testing, of verifying the method for interfacing all subsystems for real-time operation, of testing individual subsystems, and of gathering a database of meteorological and wake-vortex data for predictor algorithm refinement. Details of the AVOSS deployment at DFW (ref. 5) are shown in figure 6 and schematically in figure 7.

A successful field-test deployment of an updated AVOSS system took place at DFW in July 2000. Major enhancements included improved weather data estimates (wind, turbulence, and temperature), improved short-term (30-minute)



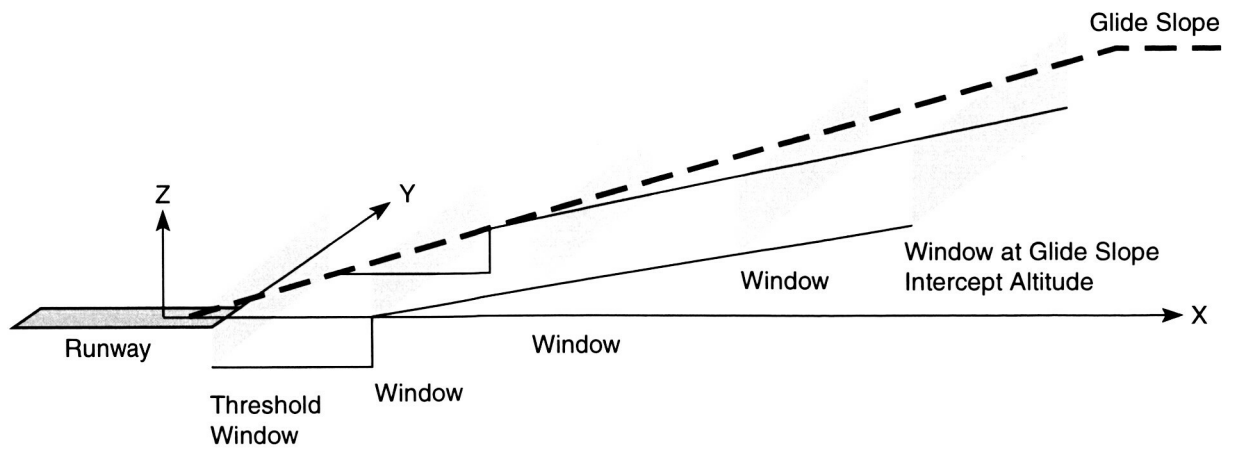


Figure 5. AVOSS approach safety corridor.

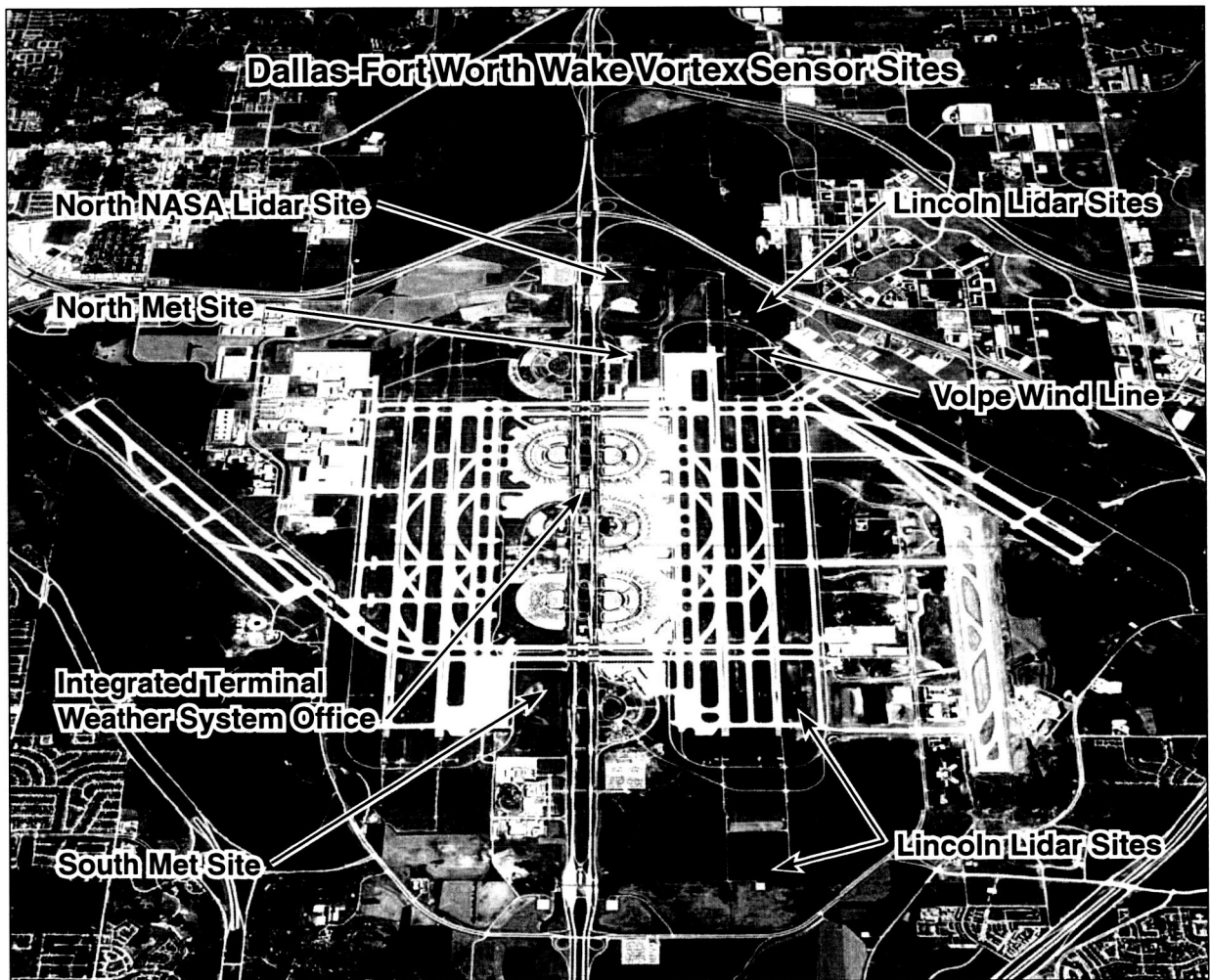
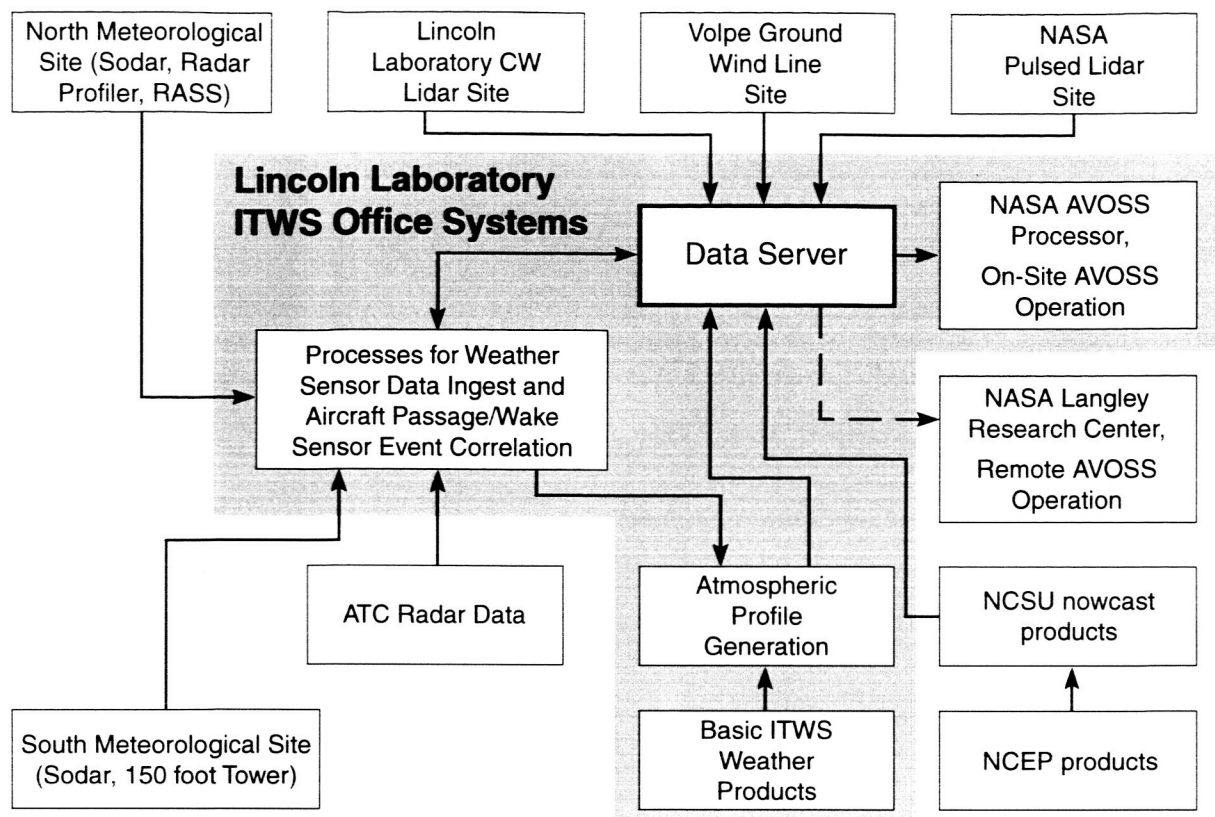


Figure 6. Field deployment of AVOSS at the Dallas-Fort Worth International Airport.



ITWS Integrated Terminal Weather System  
 NCSU North Carolina State University  
 NCEP National Center for Environmental Prediction

NOTE: Elements in the shaded area were physically located in the Lincoln office suite.

Figure 7. Schematic of the AVOSS deployment at the Dallas-Fort Worth International Airport.

forecasts of weather conditions, and improved wake sensing. The AVOSS system at DFW predicted an average arrival rate increase of 6% more aircraft per hour with a range of 1%-13%. This deployment demonstrated the maturity levels of all the systems and the conceptual feasibility in real-time operation of an engineering model AVOSS at a major airport. Technologies developed with the ground-based AVOSS system will permit safe and significant increases in airport throughput and capacity by determining and validating aircraft spacing at the top of the approach corridor that is necessary to avoid wake turbulence encounters between lead and trailing aircraft in weather conditions ranging from clear to IMC.

#### Airborne Information for Lateral Spacing

Another constraint to increasing airport capacity that is imposed at most major U.S. airports having

parallel runways that are less than 4,300 ft apart is the requirement that independent approaches to each runway be made only in visual meteorological conditions (VMC), that is, when both pilots can see the runways and the other aircraft. Today, the minimum parallel runway separation for independent instrument approaches is 4,300 ft unless a Precision Runway Monitor (PRM) is used, which enables approaches to parallel runways that are only 3,400 ft apart. In IMC at these airports, only one runway may be used for approaches or, if two runways are used, airplane spacing must be equivalent to that used for single-runway operations. The in-trail spacing plus staggered spacing (because of wake turbulence considerations) for approaches in IMC at major U.S. airports with parallel arrival runways spaced between 4,300 ft and 2,500 ft can result in a loss of arrival capacity of as much as 40% from that available in VMC conditions. The

ability to use closely spaced parallel runways simultaneously is an important enhancement to airport capacity, particularly in those situations when it is difficult to build new runways outboard of existing runways because of environmental concerns but where additional runways could be built between existing runways.

Technology was developed by NASA that demonstrates the ability to safely conduct independent simultaneous approaches in poor weather conditions to parallel runways that are 2500 ft apart. This concept, the Airborne Information for Lateral Spacing (AILS) system, was developed under the RSO sub-element and managed at NASA Langley Research Center. The goal of AILS is to safely enable independent approaches in IMC to parallel runways with centerline spacing less than 3,400 ft.

AILS technical feasibility is based on a distributed air-ground solution. The primary focus of the AILS system is to keep aircraft where they belong, on localizer and glide path through improved flight-path management via the Differential Global Positioning System (DGPS) (fig. 8). On-board

precision navigation and communications technology is applied in conjunction with robust conflict-detection algorithms to alert the crew to any potential collision situations involving another aircraft in the approach (a blunder), and provides a procedural escape maneuver that allows the flight crew to safely avoid the collision threat. The resulting safer reduced runway-separation requirements for independent parallel approaches has the potential to provide as much as a twofold increase in throughput for independent instrument flight rules (IFR) approaches to airports with closely spaced parallel runways.

NASA Langley Research Center, working in partnership with Honeywell, completed in 1999 an AILS simulation study, with a Boeing 757 simulator, examining normal and potential collision scenarios. Sixteen airline pilots served as test subjects, each paired with a research pilot acting as first officer. Auto-coupled and manual approaches to runways with centerline separation distances of 3,400 ft and 2,500 ft were studied with intrusion miss distances (distance of closest encounter), pilot reaction times, and pilot acceptability as the critical factors. The results of

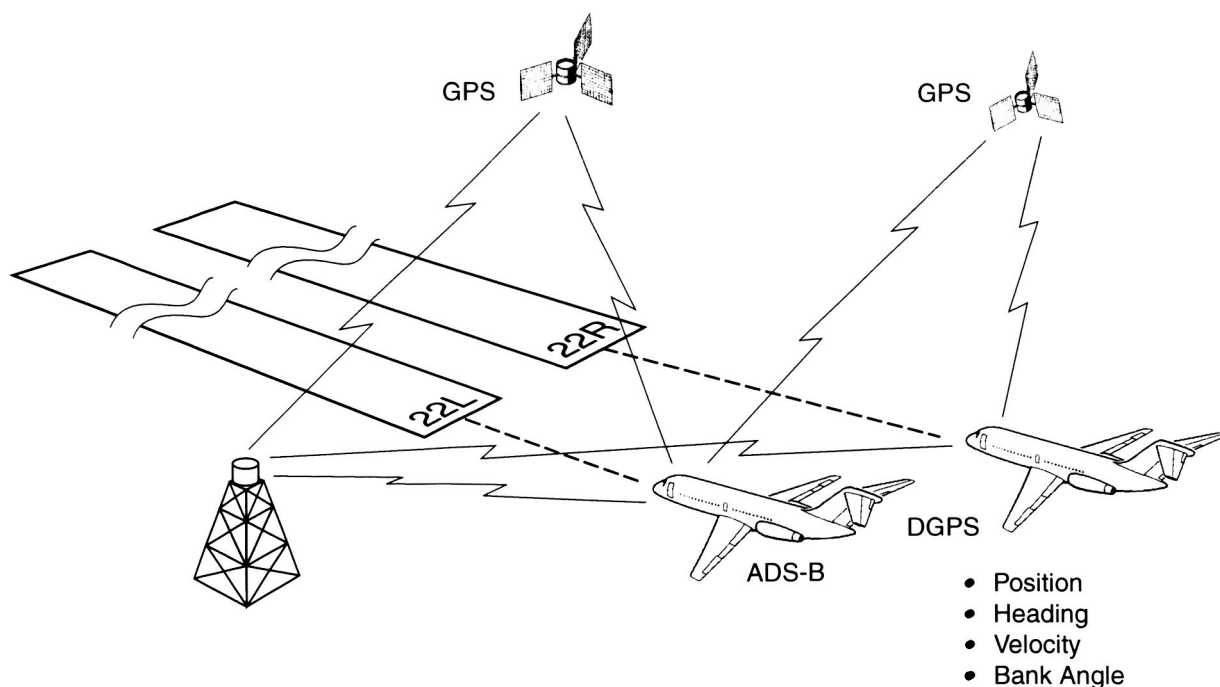


Figure 8. Schematic of AILS air-ground components.

the study supported the AILS concept: specifically, miss distances during all runs were greater than 1,000 ft, the pilot reaction times were within acceptable norms, and the AILS procedures were rated as acceptable by all test subjects.

The simulation study results were validated later in 1999 with a follow-on flight test that emulated parallel runway spacing of 3,400 ft and 2,500 ft at the NASA Wallops Flight Facility and in a demonstration at the Minneapolis-St. Paul International Airport (MSP). Both the flight test and demonstration used the NASA Langley owned Boeing B-757, uniquely configured to support research (fig. 9), and a Honeywell G-IV aircraft. Each aircraft was equipped with AILS/Traffic Alert and Collision Avoidance System (TCAS), Mode-S/ADS-B, and DGPS hardware for the flight test and demonstration.

For the flight test, six of the airline pilot test subjects from the simulation study flew a subset of the potential collision scenarios investigated in the simulation study and achieved the critical objective of simulation study validation with very similar results. Additionally, the MSP demonstration provided the opportunity to validate the AILS concept in revenue airport airspace and to provide industry and government insight into the AILS concept (ref. 6).

Later, a full mission air/ground simulation was conducted in the B-747 simulator at Ames, which is level-D certified. The subjects in the study were line pilots and Full Performance Level (FPL) controllers from Seattle-Tacoma (SEATAC) approach control. The simulation environment was Seattle Approach Control's airspace. Flight crews flew approximately 40-mile final approaches, and



Flight Deck Research Station is located on the left side of the cockpit. Flight displays and head-up display formats are generated by the Transport Research Station.

*Figure 9. NASA Airborne Research Integrated Experiments System (ARIES) B-757-200 aircraft.*

communicated with the approach and final controllers. Procedures and airspace issues were developed through our interaction with Seattle Terminal Radar Approach Control (TRACON). Flight crews responded to "at risk" blunders early, mid, late, or not at all, after being cleared for an approach. Their procedural responses to each blunder were based on the AILS alert algorithms and blunder procedure (right or left turn and climb). Flight crews communicated their action to ATC which, when appropriate, worked the aircraft back into the traffic pattern. At this point, the scenario concluded.

### **Flight Management System/CTAS Integration**

Aircraft operating in the extended terminal area are often forced by ATC to depart from their desired flightpaths. These ATC interruptions are generally required to maintain separation from surrounding air traffic. The advent of airborne flight management systems (FMS) which are capable of generating accurate and efficient flight trajectories has made the problem of ATC interruptions much more noticeable to the flight crews of modern transport aircraft. Further, ATC controllers presently do not have the information or tools necessary to separate aircraft without penalties in fuel efficiency, which adversely affects the economy of airline operations.

The Center/TRACON Automation System (CTAS) promises to provide controllers with automation tools to efficiently handle the sequencing and separation of aircraft. A key capability of CTAS is the prediction of aircraft trajectories and conflict probing of the predicted trajectories of many aircraft. In essence, CTAS provides a rudimentary flight management system capability for all aircraft in the system. Airborne FMS trajectory generation is of a higher fidelity, tailored to each specific aircraft. A mutually complimentary method of trajectory definition, both for CTAS predictions and for on-board FMS guidance, is needed for a truly integrated airspace management system. Researchers at Langley, under RSO, and at Ames, under ATM, are working together to define the level of air/ground interaction data exchange to achieve both the en route-descent fuel-saving use of airborne FMS with safe

descent separation, and to meet the Metering Fix delivery times for CTAS scheduling and flow control.

A flight test using the NASA Langley Transport Systems Research Vehicle (TSRV) Boeing 737 airplane was conducted in September 1994 at Denver, Colorado, in support of baseline CTAS development. Trajectory prediction accuracy of CTAS Descent Advisor was evaluated over several levels of cockpit automation ranging from a conventional cockpit to a performance-based vertical navigation (VNAV) flight management system. Error sources and their magnitudes were identified and measured from the flight data. Data from the flight test were provided to CTAS developers, as well as to research groups such as Seagull Technology for further analysis (ref. 7).

Later, a major simulation experiment was successfully conducted in August 2000. The experiment involved 5 weeks of joint testing with Langley RSO and Ames ATM researchers. The details of this experiment are provided below in the ATM section.

### **Low Visibility Landing And Surface Operations**

The goal of the TAP program is to increase airport terminal-area capacity. Although development of DGPS navigation, advanced aircraft FMS, and wake-vortex detection systems (such as AVOSS) contribute to the TAP goal of increasing airport throughput by reducing separation requirements for aircraft approaching an airport, they can also contribute to the congestion of surface operations as the airport arrival rate increases. The Low Visibility Landing and Surface Operations (LVLASO) sub-element of the TAP project addresses this potential problem by identifying, developing, and demonstrating technologies that can safely improve the efficiency of airport surface operations in IMC to Category IIIB (300 ft runway visual range (RVR)) and during nighttime surface operations. These improvements in surface operations will be accomplished by integrating advanced technologies, such as satellite navigation systems, digital data communications, information



presentation technology, and ground surveillance systems into the flight deck. This will enable expeditious traffic movement on the airport surface, thus reducing runway occupancy time (ROT) and improving the efficiency of taxi operations while providing flight-deck integration with FAA-evolving surface automation systems.

### Dynamic Runway Occupancy Measurement

The Dynamic Runway Occupancy Measurement (DROM) system is the first automatic system that provides accurate predictions of current ROTs by aircraft type and time of day, and for current weather conditions such as wind velocity and direction, rain/snow/clear, and RVR for each arrival and departure. DROM then determines when an aircraft's spacing on final approach is limited by ROT. DROM utilizes the data of a multilateration system that provides aircraft position and identification with mode A/C/S transponders (fig. 10) and correlates response times from aircraft transponder interrogations in order to establish aircraft position (triangulation). Other schemes use position information Global Positioning System (GPS)-equipped transponders. Using the identification and position information, DROM tracks the arriving aircraft and determines where and when the aircraft leaves the runway.

This technique does not require aircraft modification or additional equipment and is currently being considered for use in the FAA's Airport Target Identification System (ATIDS) and Airport Surface Detection System-Model X (ASDE-X) programs. It will be used as an enabling technology with AVOSS and CTAS (Center TRACON Automation System) to aid in determining required minimum miles-in-rail (MIT) spacing for arriving aircraft. DROM system functionality was fully and successfully demonstrated during field tests at the Atlanta Hartsfield International Airport (April 1996-April 1997) and was installed and operational at that airport from April 1997 to September 1997. In addition to demonstrating successful interfaces with a major airport's surface surveillance and weather systems, this deployment also provided a large body of useful current ROT data for a major airport that was used to analyze factors that determine ROT, such as aircraft weight and velocity, air carrier, and meteorological condition (ref. 8).

Current operating rules limit minimum arrival separation at the threshold to 3.0 n.mi. unless certain criteria are met. The most demanding criterion is a demonstrated average ROT of 50 sec or less. Average ROTs under 50 sec have been demonstrated at 9 of 10 major U.S. airports\* for

\* Boston Logan (BOS), New York John F. Kennedy (JFK), New York LaGuardia (LGA), Newark (EWR), Chicago O'Hare (ORD), Atlanta Hartsfield (ATL), Dallas-Fort Worth (DFW), Detroit Wayne County (DTW), Los Angeles International (LAX), and San Francisco (SFO).

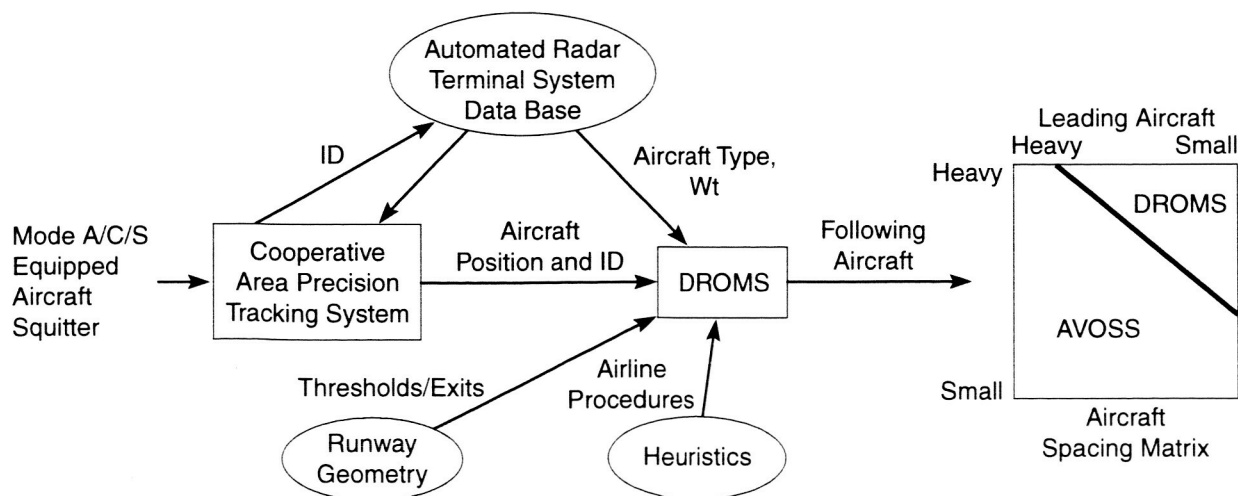


Figure 10. Schematic of the Dynamic Runway Occupancy Measurement System (DROMS).



VMC conditions and reported in a study (ref. 9) of benefits accruing from the application of TAP technologies at these airports. Although it is controller practice to revert to a separation of 3.0 n.mi. at the threshold whenever runways are wet in IMC-1 (standard IMC) and IMC-2 (low visibility, severe IMC), available IMC ROT data and pilot anecdotes strongly support the case that ROTs on wet runways are not only no longer than, and, in fact, may be shorter than ROTs on dry runways (ref. 9). It is estimated that significant benefits will result if the DROM data confirm less than 50-sec average ROTs in wet IMC-2, thus allowing a 2.5-n.mi. threshold separation.

### **Roll-Out and Turn-Off**

A system developed and demonstrated under the LVLASO sub-element is the high-speed Roll-Out and Turn-Off (ROTO) head-up display (HUD) system to assist flight crews in reducing ROT in visibility conditions to an RVR of 300 ft. ROTO is a guidance, control, and situation-awareness system that has both automatic and manual modes and focuses on developing technologies that aid pilots during the operational task of smoothly decelerating after landing and speedily steering a transport aircraft off the runway to a pre-selected exit taxiway.

In the automatic mode, ROTO-HUD will automatically select the first turnoff that the aircraft can safely make without exceeding a nominal deceleration level. If the pilot cannot decelerate in time to make the turnoff, ROTO will automatically switch to the next turnoff. In the manual mode, the pilot can select the desired exit by using the ROTO runway-selection control panel after a valid Instrument Landing System (ILS) frequency has been selected. If ROTO detects that the aircraft cannot safely decelerate to make the turnoff, the turn symbology will not be displayed. The pilot will then select the next desired exit. In the air, ROTO symbology is added to the standard HUD flight symbology. Once a valid ILS frequency has been selected and the pilot has selected the automatic or manual operating mode, a ROTO box appears in the upper right-hand corner of the HUD display that indicates the chosen runway exit, the acceptable turnoff speed,

and the nominal braking distance. Virtual cones demarcate the edges of the runway and the selected turnoff (fig. 11).

Software has been developed that produces a system of redundant deceleration cues for a pilot during landing rollout, and presents these cues on a HUD as the primary pilot/system interface. This same software produces symbology for aircraft operational phases involving cruise flight, landing, rollout, and takeoff. It is part of a larger Integrated Display System (IDS) developed for the LVLASO project which collects, processes, and presents information to the flight crew on both a liquid-crystal head-down display (HDD) and a HUD. The IDS software was successfully flight tested on board NASA's B-757-200 research aircraft and was demonstrated at the Atlanta Hartsfield International Airport in August 1997 (refs. 10-12). The flight test was a cooperative effort with the FAA's Runway Incursion Reduction Program (RIRP) and demonstrated a prototype system consisting of several advanced technologies that made up an integrated communication, navigation, and surveillance system. It validated the operational concept, assessed technology performance, and demonstrated successful technology integration aimed at safely increasing the traffic capacity of the airport surface moving area. A summary of the IDS software is available (ref. 13) as are software products, system architectures, and operational procedures developed by Lockheed-Martin in support of the ROTO sub-element (ref. 14).

By itself, ROTO is not expected to have a major effect on arrival capacity because MIT separations rather than ROT historically determine minimum interarrival times in IMC-2. If used in conjunction with DROM, however, ROTO may enable, and DROM confirm, average ROTs of less than 50 sec in severe IMC-2, thus allowing 2.5-n.mi. MIT separations for all levels of IMC. If this proves to be the case, ROTO will provide significant additional benefits.

A study conducted in the Visual Motion Simulator at Langley, using advanced ROTO symbology and guidance, evaluated display configurations using minimal symbology such as runway exit

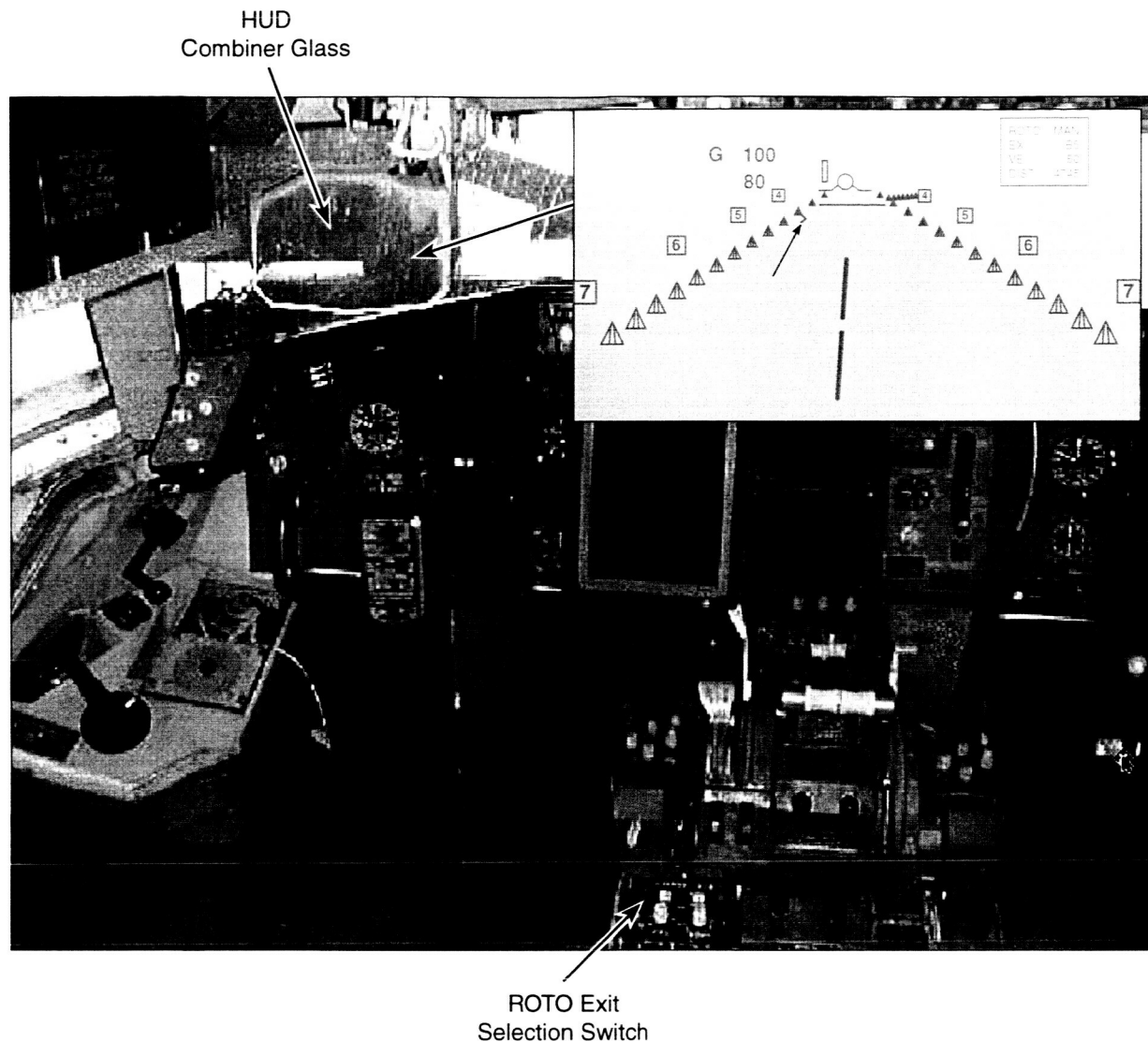


Figure 11. ROTO-HUD symbology in flight deck.

edge and centerline markings at 1,200 ft RVR, 300 ft RVR, and in clear-weather conditions. A total of 13 airline, corporate jet, and research pilots participated in the simulation that examined their ability to decelerate aircraft and turn off runways onto a desired exit more efficiently. Half the runs were conducted using the ROTO-HUD guidance and half without. The pilots indicated that the system was easy to use, and the results showed that the mean ROT was reduced by 13% at 1,200 ft RVR and by 28% at 300 ft RVR using the ROTO system. The study results demonstrated the effectiveness of the ROTO system for reducing

ROT and improving airport surface capacity throughput.

#### Taxiway Navigation and Situation Awareness

In 1997 the International Civil Aviation Organization (ICAO) proposed the development of a modular system to support safe, orderly, and expeditious movement of aircraft and vehicles on airport surfaces under all circumstances, including low-visibility conditions. This was brought about as a result of an increase in the number of surface incidences, the increasing complexity of airports, the increasing number of operations, and the desire

to maintain capacity in all-weather conditions. A set of guidelines was provided that would support safe and efficient gate-to-gate operations (ref. 15).

Concurrent with the ICAO's proposed system development, the Human Factors Research and Technology Division at Ames Research Center developed a proposed Taxiway Navigation and Situation Awareness (T-NASA) cockpit display suite which included an electronic moving map (EMM), scene-linked head-up display (HUD), and directional auditory traffic alerts. These displays were coupled with a communication, navigation, and surveillance (CNS) system developed by NASA, the FAA, and industry and university partners which addressed the ICAO requirements of providing surveillance, routing, guidance, and control.

A series of focus groups was conducted to evaluate the future deployment of T-NASA, as well as that of the AILS, ROTO, and CTAS/FMS TAP technologies (refs. 16, 17). The focus groups consisted of pilots from six commercial airlines and air-traffic controllers who viewed a training video describing the display components and procedural assumptions. Afterwards, they discussed how these displays may alter their current standard operating procedures and what procedural implications T-NASA may have on their daily operations.

T-NASA focuses on technology aimed at helping pilots navigate on the airport surface in low-visibility conditions and at night by providing the path of a cleared taxi in/out route, thus making taxiing safer and reducing the amount of time an aircraft needs to spend on the runway. It has three major components: an EMM, which is an airport taxi chart with route and own-ship and traffic location; scene-linked symbology which is route/taxi information virtually projected by a HUD onto the forward scene; and a three-dimensional (3-D) audio ground collision-avoidance navigation system which has spatially localized auditory traffic and navigation alerts. Figure 12 shows a cockpit display suite for T-NASA in the Ames Advanced Simulator Cab.

A flight demonstration and field evaluation of an advanced T-NASA system was conducted at the Atlanta Hartsfield International Airport in August 1997 in cooperation with the FAA. The demonstration integrated both airborne and ground-based technology and components to provide the flight crew and controllers with additional information to enable safe, expedient surface operations. The airborne T-NASA system included a panel-mounted electronic taxi map display (EMM) and a scene-linked HUD, both of which were installed and flight tested in NASA's B-757 research aircraft, and GPS data links. The ground-based technology included surface surveillance systems, airport traffic identification, ATC interface, and data links.

Four B-757 captains from four different commercial airlines and NASA test pilots participated in the flight evaluations. A crew consisted of one commercial airline captain responsible for the aircraft during landing and taxiing, and two NASA test pilots, one acting as first officer and the other as an observer. The results demonstrated that the T-NASA system and the supporting technology infrastructure could successfully be implemented at a major airport facility, as well as validating the utility of the T-NASA system in the context of normal handling conditions at a major airport facility.

Demonstrated benefits included improved low-visibility surface navigation, increased surface situational awareness in low-visibility conditions, runway incursion avoidance, and reduced runway occupancy time. The commercial pilots reported that T-NASA technology could improve terminal-area productivity and that the EMM and HUD reduced total taxi time, increased taxiing safety, and reduced mental navigation workload while taxiing. Details of the test methods used, results of the investigation, and commercial pilots post-test comments and statements regarding the T-NASA system are documented in reference 18.

The T-NASA suite of cockpit displays for low-visibility operations developed by NASA researchers was guided by a human-centered design approach to ensure that the system would

### HUD

### COMMUNICATIONS

ATC datalink routes and control directives to the cockpit. Pilots acknowledge via datalink response buttons.

### SURVEILLANCE

Ground-based system detects aircraft location and presents traffic on EMM.



### NAVIGATION

T-NASA HUD and EMM rely on DGPS and an accurate airport database.

*Figure 12. T-NASA Cockpit Display Suite in the Ames Advanced Concepts Simulator Cab.*

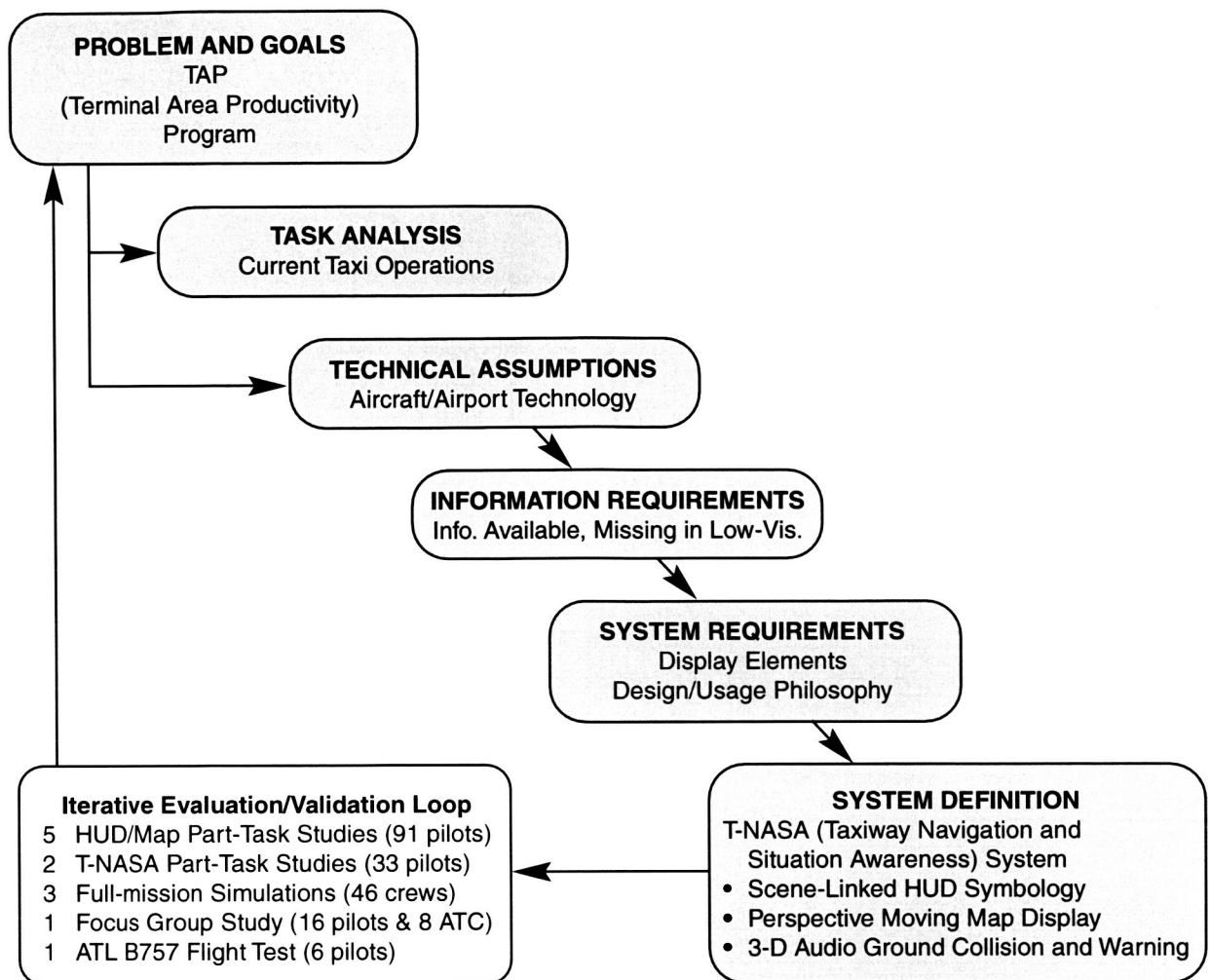


Figure 13. An illustration of the Human-Centered T-NASA design process.

not only meet its objectives of increased efficiency and safety but would, at the same time, consider not only the capabilities and limitations of the flight crew but also the problems and issues associated with current taxi operations from a pilot's perspective. The design approach further assumed that aircraft in the future will be equipped with data-link technologies permitting controller-pilot communication thereby allowing ATC to issue routing and control instructions and to provide ground-based surveillance data to ATC and to any data-link-equipped aircraft. The T-NASA human-centered design process has, over time, involved more than 300 commercial pilots participating in part-task simulations, high-fidelity simulations, and flight tests at the Hartsfield

International Airport in Atlanta, Georgia. This human-centered design process is discussed in reference 19 and illustrated in figure 13.

Indicative of this human-centered design approach is a simulation of an advanced T-NASA cockpit display suite performed in the high-fidelity Advanced Concepts Flight Simulation (ACFS) facility at Ames Research Center (fig. 14) to evaluate the effects of an EMM and a HUD on ground taxi performance in reduced-visibility conditions. The ACFS facility emulates a wide-body, T-tail, low-wing aircraft with twin turbofan engines. The participants were 32 highly experienced pilots consisting of 16 captains and 16 first officers recruited from commercial airlines and

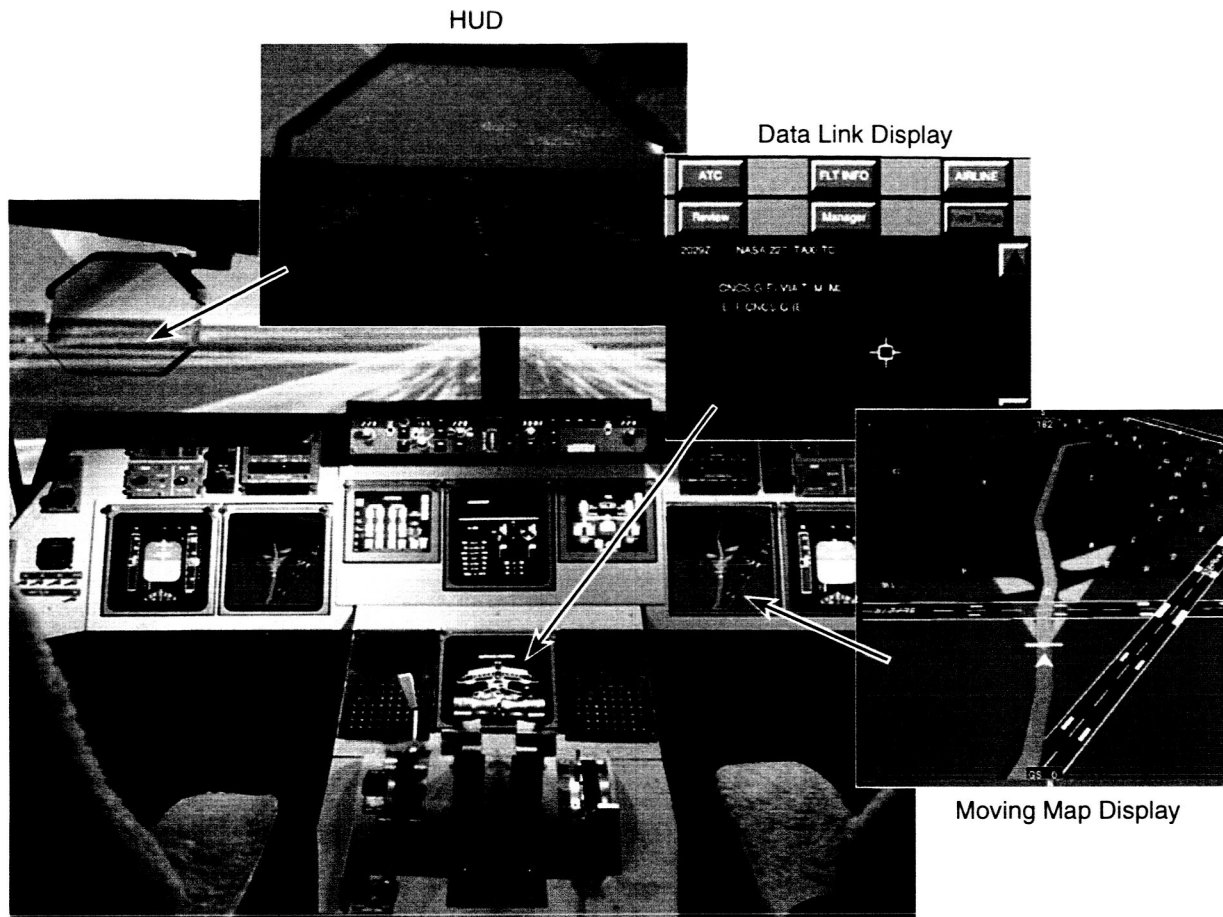


Figure 14. A T-NASA simulation cockpit display suite showing a HUD, a moving map, and a datalink display.

currently flying glass-equipped Boeing 757s, 767s, 747-400s, or 777s. Twenty-one trials were completed in the simulation, which took advantage of the results of the earlier Atlanta Hartsfield International Airport flight demonstration, each trial consisting of an autoland arrival to the Chicago O'Hare airport and taxi to an apron area in 1,000 ft RVR conditions.

Upon completion of the simulation, the pilots rated the benefits of T-NASA in improving their ability to accurately navigate on the airport surface. Relative to a baseline condition, the EMM/HUD combination increased taxi speed by 16% (from 13.9 knots in current day operations to 16.1 knots with T-NASA), and reduced navigation errors by nearly 100%. Pilot responses indicated that the EMM was particularly advantageous because it

gave them a greater awareness of route, greater confidence in their position on the airport surface, and more efficient communication between crew members, and because it reduced the time required to plan the route. These results, together with workload and situation-awareness ratings, analysis of crew interactions, and pilot feedback (ref. 20), provide strong evidence that the combination of the EMM and a HUD can substantially improve both the efficiency and safety of ground operations.

### Air Traffic Management

The Air Traffic Management (ATM) sub-element of the TAP project addresses the technology necessary for real-time, two-way interaction of the Center Terminal Radar Approach Control (TRACON) Automation System (CTAS)



with aircraft flight management systems (FMS). The goal of ATM is to build upon existing CTAS technologies to develop supplementary automation tools to improve terminal-area productivity. These include increasing capacity by reducing separation buffers in current operations without compromising safety, providing the technology permitting users the flexibility to choose desired routes, and improving efficiency by allowing maximum use of FMS.

### **Final Approach Spacing Tool**

NASA Ames Research Center, under its Advanced Air Transportation Technologies (AATT) project, but still within the ASC program, conducted enabling research in three of five areas in support of the FAA's Free Flight Phase 1 (FFP1) program. The FFP1 program has as its goal the modernization of the national airspace by developing technologies that will permit free-flight operations in the near future. One of these technologies is the Final Approach Spacing Tool (FAST). Although not an element of the TAP project, the FAST is used as an element supporting ATM and as a cost-benefits parameter for implementing the TAP technologies. Designated passive and active (pFAST and aFAST, respectively), they are decision support tools intended to permit more efficient use of arrival and departure runways during periods of peak loads.

The pFAST makes decision support and management tools available to TRACON controllers and traffic management coordinators (TMCs) by providing landing sequences, landing runway assignments, and turn, speed, heading, and altitude advisories to assist controllers in accurately vectoring aircraft onto the final approach along conflict-free paths. A NASA prototype is installed and in use at the DFW airport.

The aFAST is a follow-on to the pFAST and is being developed to achieve more accurate aircraft separation on final approach by use of a data link to exchange information between air and ground and to uplink FAST-computed route-modification clearances. In TRACON airspace, this will include route-modification clearances from the downwind leg to the final approach fix; it will also provide

active advisories, including heading and speed, and will generate sequencing and scheduling information. A 10% additional capacity improvement over pFAST is expected. Providing air carriers with this improved predictive information about their arriving flights and given the ability to alter arrival times to prevent timing miscues can provide a potential annual savings of \$75 million.

There are two remaining technology areas in which Ames Research Center is conducting research under the AATT project in support of the FAA's FFP1 program:

1. Traffic Management Advisory-Single Center (TMA-SC) which provides ATC with en route information that will reduce airspace system delays by increasing the arrival throughput and efficiency of air traffic operations in the terminal airspace.
2. The Surface Movement Advisor (SMA) which facilitates the sharing of aircraft arrival information with airlines to aid decision making regarding the surface movement of aircraft.

As of August 2001, FAST, TMA and SMA are deployed and operational at major airports and FAA Centers throughout the country as part of the FFP1 program (fig. 15).

### **CTAS/FMS Integration**

The Center-TRACON Automation System (CTAS) was conceived and prototyped at Ames Research Center. It is a new approach to air traffic control and was designed to better help controllers manage the increasingly complex air-traffic flows at large airports. In 1991, the CTAS was selected by the FAA as the future automation system for the terminal area. The integration of CTAS with onboard Flight Management Systems (FMS) is a major joint technology development within the ATM and RSO sub-elements of the TAP project. Conceptually, the CTAS/FMS integration provides the controllers and pilots with the ability to use data-linked text messages instead of voice messages. These messages, when accepted by the pilot, are integrated into the FMS and, based on the pilots decision, are logged and executed by the FMS.



Currently three main automation decision support tools have been developed that allow FMS trajectories to be flown in Center and TRACON airspace. These are (1) the Traffic Management Advisor (TMA), which is a sequence and scheduling tool that predicts the trajectories of arriving aircraft in order to accurately estimate when aircraft should arrive at meter fixes on the TRACON boundary; (2) an en-route Descent Advisor (DA), which is a Center (Air Route Traffic Control Center (ARTCC)) tool developed for air traffic controllers and designed to provide a conflict-free, fuel-efficient trajectory for each arriving aircraft resulting in the aircraft arriving at the TRACON meter fix at the TMA scheduled time; and (3) a Final Approach Spacing Tool (FAST), which provides runway assignments and sequence advisories in TRACON airspace, accurately vectoring aircraft onto the final approach along conflict-free paths.

The TMA has been evaluated at the Dallas-Ft. Worth ARTCC, and the en-route DA was evaluated at the Denver ATC ARTCC in 1994-1995. A "passive" version of the FAST (pFAST) was evaluated at the Dallas-Ft. Worth TRACON; its effect on model parameters is discussed in reference 8. Included is the rationale for adding an inefficiency buffer which would model the situation where a following aircraft cannot take advantage of the minimum safe spacing between pairs of aircraft landing on the same runway. The buffer is intended to simulate the effect of nonoptimum runway balancing and sequencing.

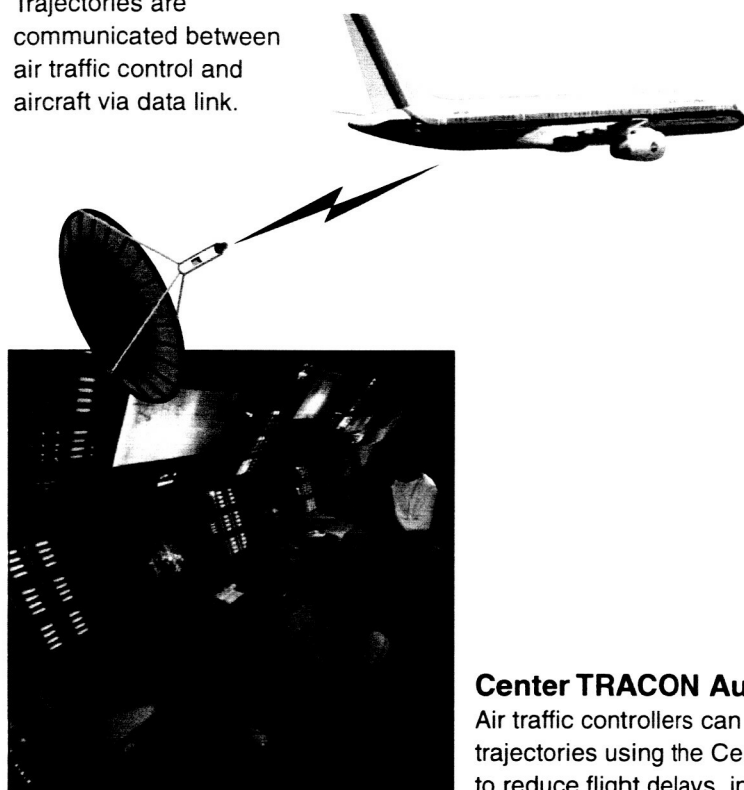
In the far-term, the CTAS/FMS systems will incorporate data-link capabilities to exchange information between air and ground and to uplink route-modification clearances (figs. 16 (a) and 16 (b)). It is assumed that Automatic Dependent Surveillance-Broadcast (ADS-B) information, on aircraft position, vertical velocity, track angle, and estimated time of arrival, will be available to the ground. This improved information will allow CTAS to make accurate predictions of the aircraft's four dimensional (4-D) trajectory (position plus time) and will improve the precision and timeliness of information on the controller's plan view display.

An analysis was performed (ref. 8) wherein two levels of CTAS/FMS integration were modeled. The first was ATM-1 with a 3-D (position only) FMS permitting the aircraft to transmit its precise position, velocity, and intended path to the CTAS. Using those data, the CTAS, when equipped with the aFAST, can provide more accurate cues to the controller. The ATM-2 level of CTAS/FMS integration provides a 4-D (position plus time) FMS. In addition to the 3-D information, the 4-D FMS can provide the CTAS with accurate estimates of threshold crossing time. ATM-2 expands beyond the aFAST and assumes direct flight planning interaction between the CTAS computer and the aircraft FMS. Potential benefits from both levels of the CTAS/FMS are quite substantial. However, the aFAST has neither been tested at an airport, nor is it yet planned for deployment; as a result, a second baseline having a more limited passive FAST (pFAST) technology was also used in the model analysis.

In the far-term, the CTAS/FMS makes possible the use of data-link capabilities to facilitate data and information exchange between the CTAS and FMS in three major application areas:

1. CTAS/FMS data exchange between ATC and the cockpit permit prediction of aircraft trajectories with a high degree of accuracy in real time. This allows reduction of separation buffers that are artificially introduced to account for inaccuracies, improving both traffic capacity and downlink of aircraft state information to controllers. This permits tighter tolerances when monitoring and controlling air traffic.
2. FMS operation in the TRACON provides the ability for ATC to uplink a complete trajectory clearance to the cockpit where it can then use the FMS to accurately track the cleared trajectory and further reduce extra separation buffers introduced to account for inaccurate manual tracking.
3. FMS operation in the Center (ARTCC) transition airspace for arrivals, improves the ATC system's ability to accommodate user-preferred routes. This will improve user flexibility and allow controllers to handle more

Trajectories are communicated between air traffic control and aircraft via data link.



### Cockpit Automation

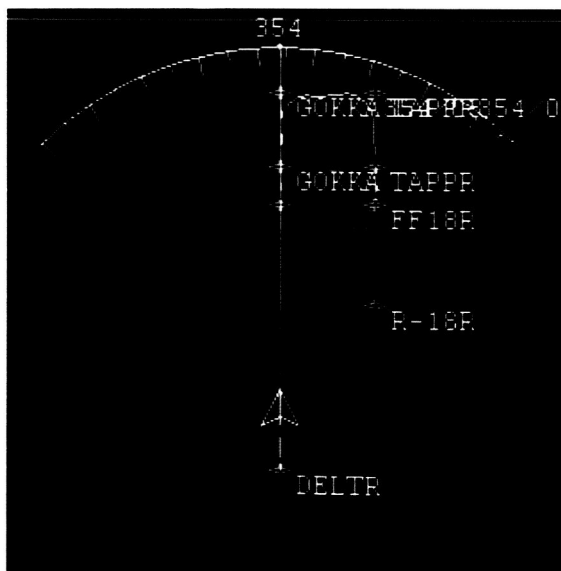
Flight crews can follow these trajectories accurately using the aircraft's FMS automation.

### Center TRACON Automation System CTAS

Air traffic controllers can determine the optimal modifications to the trajectories using the Center TRACON Automation System (CTAS) to reduce flight delays, increase throughput and ensure flight safety.

Figure 16(a). Piloted simulation with CTAS integration with onboard flight management system.

### Cockpit NAV Display



### ATC CTAS Display



Figure 16(b). Illustration of CTAS-generated approach clearances being uplinked to approaching aircraft in TRACON (concluded).

traffic without delay, significantly decreasing the average time it takes for aircraft to fly the last few hundred miles to a meter fix on the TRACON boundary, improving operational efficiency.

A major CTAS/FMS integration simulation experiment was successfully conducted in August 2000. The experiment involved 5 weeks of joint testing with NASA Langley RSO and Ames ATM researchers. A total of 10 two-person crews of airline pilots participated at Langley, flying the B-757 Research Flight Deck (RFD) simulator during the experiment. Additional airline crew test subjects participated at Ames in the Advanced Concepts Flight Simulator (ACFS) cockpit. Both flight simulators were connected in real time to the CTAS simulation at Ames, manned by ATC controller test subjects. Up to 11 test subjects (4 pilots and 7 controllers) were involved in any given simulation scenario.

A total of 34 (of a possible 40) successful test runs were conducted by the Langley RFD during the experiment. Six of the test runs were aborted or cancelled because of simulation problems at Langley or at Ames. All of the test subjects at Langley were able to fly at least one Center and one TRACON scenario. Most test subjects were able to fly a complete set of four runs.

Preliminary results from the experiment indicate that the major objectives of the test were achieved. A primary goal of CTAS/FMS integration is to increase landing capacity by reducing the dispersion in arrival times of the individual aircraft. Earlier studies at Langley and Ames indicated that keeping an airplane on its FMS lateral path (coupled in lateral navigation (LNAV)) all the way to final approach has a first order effect on reducing arrival-time error and increasing landing capacity. The TRACON CTAS/FMS procedures in this study were designed to enable the use of LNAV in the TRACON. Of the 34 successful test runs flown by the RFD, 26 were completed with LNAV used all the way to final approach. Standard FMS transitions, which can be flown by current-generation FMS-equipped

aircraft, were flown in 17 of the 26 LNAV runs. The remaining 9 successful LNAV transitions were flown using the new data-link procedures.

Pilot comments were also quite favorable. Most pilots felt the procedures for the CTAS/FMS integration were acceptable, or could be made so with minor modification. The pilots were comfortable with using the FMS throughout the descent and approach in the TRACON. The major concern was the phraseology of the verbal and data-link clearances. In particular, the altitude limits of the verbal and data-link FMS arrival and transition clearances were sometimes confusing. Several good suggestions were provided by the pilots concerning ways to clarify the altitude clearance limits. Timing of the data-link clearances, which often occurred during handoff from one controller to the next, was also somewhat of a problem. The pilots were accustomed to switching ATC frequencies, and handled the multiple tasks with little problem. Many pilots, however, were uneasy over the controller awareness of the data-link status, especially when a data-link FMS transition clearance was received during a hand-off to the next controller. They were not sure the next controller was aware of the data-link clearance or how to handle the verbal check-in with the next controller while they were simultaneously processing the data link. Most of the pilots felt these were general data-link issues and most had no problems with the CTAS/FMS integration aspects of the data link.

The en route cruise and initial descent CTAS/FMS integration procedures also worked well in this experiment. The pilots were comfortable with the wind uplink from the CTAS and had no problem with the "descend via..." at the VNAV top of descent. Several speed and route change data-link messages were received by each crew and were handled without problems or confusion. There was some concern over the lack of detail in the route-modification data-link message and the possibility of not knowing what the actual uplinked route or crossing restrictions were if the uplink modification was inadvertently changed or erased before execution.

## Air-Air Traffic Control Systems Integration

The cost-benefits analysis sub-element under the Air-Air Traffic Control Systems Integration (AASI) technology element of the TAP project was conducted for the purpose of providing a sound basis of technical and economic information that could be used (1) by NASA in making future internal programmatic decisions and (2) by the FAA and the airlines in making decisions regarding the further development and implementation of the TAP technologies. Four TAP technology elements were considered: the AVOSS, DROM, ROTO, and ATM. NASA elected not to include the AILS and T-NASA since it was determined that

benefits accruing from AILS could be estimated by a straightforward modification of the current models and that those of the T-NASA could be estimated by adding taxi queues to the current models. The Integrated Technology Demonstrations and the Procedure and Safety Substantiation sub-elements of the AASI project were cancelled by NASA because of funding constraints. Cost models have been previously developed for the TAP technologies (ref. 21).

### Analysis Approach

The basic approach used to estimate the cost benefits that could be accrued in implementing the TAP technologies is summarized in figure 17. Arrival delays are estimated by first calculating

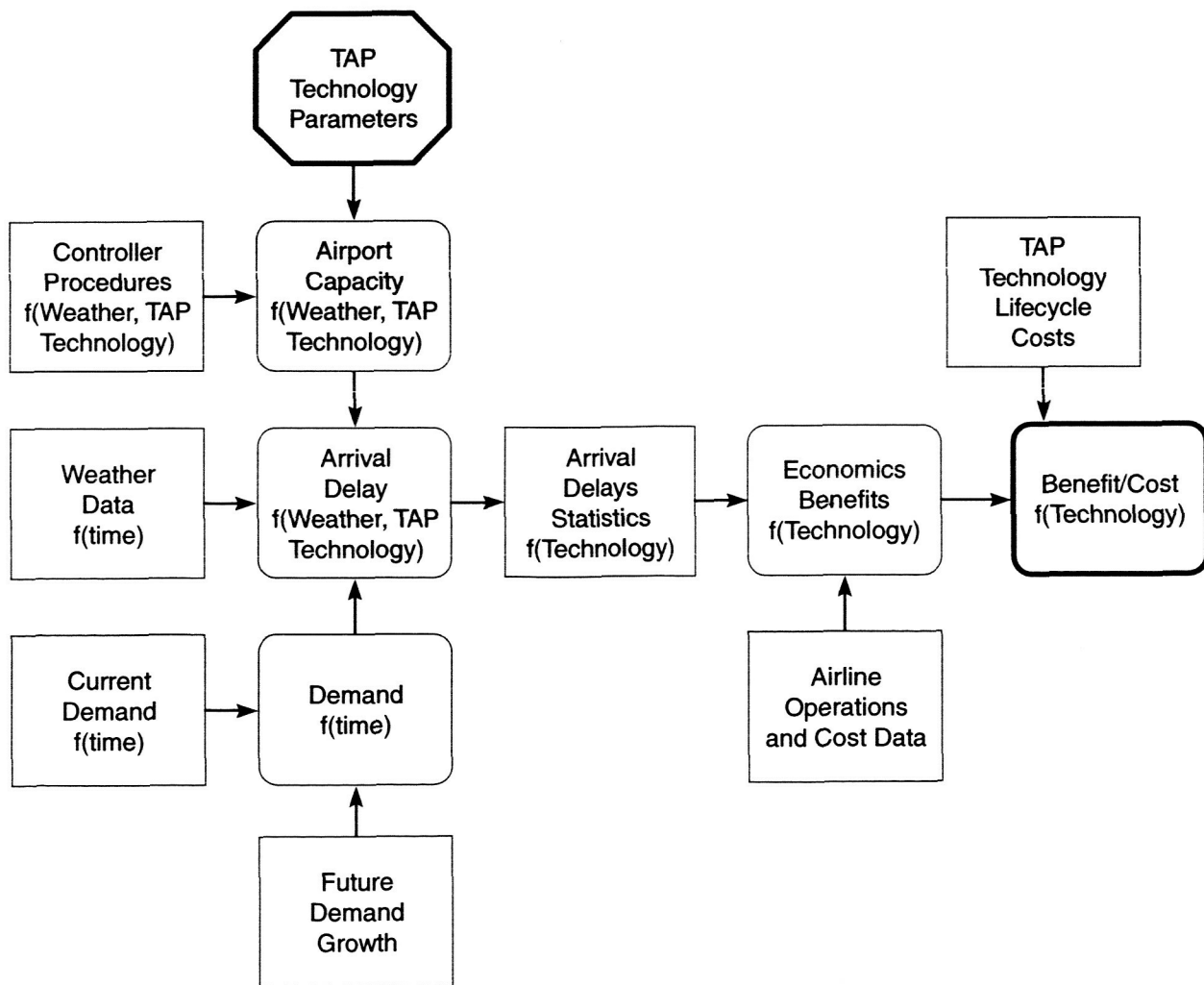


Figure 17. Basic approach used to estimate the cost benefits accrued of implementing the TAP technologies.



airport capacity as a function of runway configurations, weather-related ATC operating procedures, and TAP technology levels. Weather data are used to determine which runway configurations are legal, based on ceiling and visibility, and usable, based on crosswinds and tailwinds. Runway capacity data of the legal/usable runways are used to determine an airport's capacity at a given hour. If the arrivals and departures exceed the capacity of any runway for any operating hour, the resulting delay is calculated for that runway. Second, future hourly demand is estimated based on current hourly demand adjusted by growth predictions contained in the FAA Terminal Area Forecast (TAF). Capacity is then estimated along with projected airport hourly departure and arrival demand information which, together with historical weather data, is used by an airport delay (queuing) model to generate arrival delay statistics as a function of TAP technology. The cost per minute of delay derived from historical airline data is then used to estimate the dollar value of the reduced number of arrival delays generated by the TAP technologies. Lastly, the estimated savings are compared to the estimated life-cycle costs for the TAP systems in order to produce benefit-to-cost ratios. The TAP technologies affect the capacity and delay elements by means of the capacity model input parameters and then model the process used by controllers to establish aircraft spacing. They are based on information that is available to controllers, including minimum allowed aircraft separations, runway occupancy times, and uncertainties in approach speed and aircraft position. The modeling parameters and their values chosen for the TAP analysis are given in reference 8.

### **Cost-Benefits**

Results indicate that the TAP technologies will generate substantial benefits for the airlines in terms of reductions in direct operating costs resulting from fewer arrival delays. The cost-benefits of the TAP technologies were estimated, assuming that they would be deployed at 10 major U.S. airports by the year 2005 and that they would be operational from 2006 through 2015. The 10 airports are Boston Logan (BOS), New York John F. Kennedy (JFK), New York LaGuardia (LGA), Newark (EWR), Chicago O'Hare (ORD), Atlanta

Hartsfield (ATL), Dallas-Fort Worth (DFW), Detroit Wayne County (DTW), Los Angeles International (LAX), and San Francisco (SFO).

The TAP technologies were compared with the technology baseline expected to exist in 2005. This included the assumption that GPS technology would be in place at the airports and that it would result in reductions of position uncertainty from the current 2.5 n.mi. to 100 ft. Curved approach paths were also assumed, enabling an effective reduction in the common path of 1 n.mi. However, it was noted that controllers would not be able to take full advantage of GPS-generated data for increased position accuracy since such information would have to be transmitted to the ground in such a way as to be immediately usable by the controllers. Active FAST (aFAST), a necessary base for the CTAS/FMS Integration technology, and an Automatic Dependent Surveillance (ADS) data link would be necessary to make use of the increased position accuracy resulting from GPS-generated data.

Benefits are measured in terms of time saved by reductions in arrival delays effected by the TAP technologies at the 10 airports. The benefits were analyzed for the 19 modeling scenarios shown in table 1 for the period 2006 through 2015. These scenarios include a current technology scenario and two 2005 baseline scenarios. One 2005 baseline represents the CTAS with pFAST and the other represents the CTAS with aFAST. TAP technologies were then added to these baselines. The results are expressed as discounted dollars using a 1997 base year and 7% discount rate and the inflated then-year savings using a 2.56% escalation rate. Tables 2 (inefficiency buffer = 0) and 3 (nominal inefficiency buffer) show the minutes of delay avoided by using the TAP technologies; the minutes saved are then expressed in terms of 1997 constant-dollar value. The pFAST and aFAST baseline savings are relative to the current technology. The TAP technology savings are relative to the pFAST and aFAST baselines. The 10-year savings owing to pFAST range from zero, when the inefficiency buffer is zero, to \$3.7 billion, when buffers are applied to all airports; the savings for the lower risk DROM, ROTO, and

TABLE 1. MODELING SCENARIOS USED TO ANALYZE BENEFITS OF ARRIVAL DELAY SAVED BY TAP TECHNOLOGIES.

Title	Baseline	Content
Current Technology 2005 PFAST Baseline	n/a CT	Current Technology PFAST
PFAST DROM	PFAST	DROM
PFAST ROTO DROM	PFAST	ROTO + DROM
PFAST AVOSS	PFAST	AVOSS
PFAST AVOSS DROM	PFAST	AVOSS + DROM
PFAST AVOSS DROM ROTO	PFAST	AVOSS + DROM + ROTO
2005 AFAST Baseline	CT	AFAST
AFAST DROM	AFAST	DROM
AFAST ROTO DROM	AFAST	ROTO + DROM
AFAST AVOSS	AFAST	AVOSS
AFAST AVOSS DROM	AFAST	AVOSS + DROM
AFAST AVOSS DROM ROTO	AFAST	AVOSS + DROM + ROTO
ATM-1 CTAS/3DFMS	AFAST	AFAST + 3DFMS + data link
ATM-1 ROTO DROM	AFAST	ATM 1 + ROTO + DROM
ATM-1 DROM AVOSS	AFAST	ATM-1 + DROM + AVOSS
ATM-1 ROTO DROM AVOSS	AFAST	ATM 1 + ROTO + DROM + AVOSS
ATM-2 CTAS/4DFMS	AFAST	AFAST + 4DFMS + data link
ATM-2 ROTO DROM AVOSS	AFAST	ATM-2 + ROTO + DROM + AVOSS

AVOSS with the pFAST TAP technologies are of the order of several millions of dollars a year for the 10 years. The 10-year savings owing to the aFAST would be substantial and would range from \$3.1 billion to \$8.1 billion depending on buffer assumptions.

The cost-benefits shown in tables 2 and 3 are for reduced arrival delays only. It should be noted that additional benefits could accrue if, for example, reduced departure delays, passenger costs, increased airline revenue, delayed need for major airport capital improvements, or avoidance of new airport construction were considered.

The potential TAP technology benefits are based on the following assumptions:

1. The AVOSS will reliably confirm the modeled wake-vortex separation reductions for the

weather criteria used (wind, turbulence, and temperature).

2. DROM will demonstrate average runway arrival times of less than 50 sec.
3. Controllers will use 2.5 n.mi. minimum separations in IMC Category 1 based on DROM data.\*
4. ROTO will enable runway occupancy times of less than 50 sec in low visibility IMC Category 2 and 3 conditions.
5. Controllers using the CTAS Active Final Approach Spacing Tool with a data link can exploit reduced uncertainties in aircraft speed and position to reduce separation.
6. The flight plans produced by integrated CTAS and FMS computers can be safely accepted and executed by controllers and pilots.

\* Categories 1, 2, and 3 correspond to decreasing levels of ceiling and visibility.



TABLE 2. TEN YEAR COST AVOIDANCE IN 1997 CONSTANT DOLLARS  
IN MILLIONS; INEFFICIENCY BUFFER ZERO.

Scenario	Compared to	Total	ATL	BOS	DTW	DFW	ORD	JFK	LGA	LAX	EWR	SFO
PFAST baseline	CT	0	0	0	0	0	0	0	0	0	0	0
PFAST DROM	PFAST	601	76	139	73	59	167	3	38	43	3	0
PFAST ROTO DROM	PFAST	1,359	136	165	87	190	447	45	88	146	16	39
PFAST AVOSS	PFAST	1,607	405	185	138	131	268	73	43	210	102	51
PFAST DROM AVOSS	PFAST	2,183	468	332	194	188	435	75	78	253	110	51
PFAST AVOSS DROM ROTO	FFAST	2,958	521	360	209	317	731	122	123	367	118	91
AFAST baseline	CT	3,088	604	225	167	358	490	84	117	783	179	81
AFAST DROM	AFAST	541	57	145	54	52	161	1	26	40	6	0
AFAST ROTO DROM	AFAST	1,171	89	174	68	140	430	36	62	124	10	38
AFAST AVOSS	AFAST	1,335	279	179	110	104	244	62	30	199	91	38
AFAST DROM AVOSS	AFAST	1,839	324	326	157	153	394	63	52	238	96	38
AFAST AVOSS DROM ROTO	AFAST	2,471	353	355	172	237	666	103	84	324	100	76
ATM-1 CTAS/3DFMS	AFAST	1,816	269	140	105	235	313	64	56	484	104	47
ATM-1 ROTO DROM	AFAST	2,766	343	306	164	324	693	96	103	539	112	84
ATM-1 DROM AVOSS	AFAST	3,368	532	444	263	345	606	126	89	677	207	79
ATM-1 AVOSS DROM ROTO	AFAST	4,056	579	525	281	405	915	163	126	735	211	116
ATM-2 CTAS/4DFMS	AFAST	3,596	529	297	210	426	634	133	106	951	220	91
ATM-2 AVOSS DROM ROTO	AFAST	5,488	750	791	349	529	1,086	218	153	1,146	312	154

The TAP benefits for the 10 major airports varied significantly at each of the airports indicating that there is no common method for projecting TAP benefits to airports in general. This is a result of differences in individual airport volume and operating conditions and indicates the necessity of accurately modeling individual airports. The methods used to estimate potential benefits, a summary of the results, the computer program, data bases, programming techniques, appendixes which address input parameter selection, model algorithms and structure, and a user's guide are reported in reference 8.

### TAP Implementation

The TAP systems and displays currently being developed are conceptual and are generally at the "laboratory" stage of development. Their continued development from the laboratory to everyday use in flight operations is necessary for introduc-

tion of TAP-specific hardware and software into the air traffic system or into the commercial aircraft fleet; and this issue must be addressed. This will necessarily be accomplished by retrofitting existing systems and will be complex and expensive. To be considered are the technical, regulatory, and cost implications, as well as how their use will affect everyday flight procedures and operations. Involved is a change in data flow for displays, the addition of a HUD, and the potential upgrading of various aircraft sensors for various aircraft types in order to provide the data accuracy and resolution required for the display of TAP information. Even more complex will be integrating TAP with existing aircraft systems that typically have many interconnections for functional performance and for internal monitoring; it is likely that the development of new software for integration of TAP functionality into the existing systems will be required. These issues were investigated and are discussed in references 15 and 16.

TABLE 3. TEN YEAR COST AVOIDANCE IN 1997 CONSTANT DOLLARS  
IN MILLIONS; NOMINAL INEFFICIENCY BUFFERS.

Scenario	Compared to	Total	ATL	BOS	DTW	DFW	ORD	JFK	LGA	LAX	EWR	SFO
PFAST baseline	CT	3,666	647	267	234	609	375	110	171	769	228	255
PFAST DROM	PFAST	613	84	139	81	62	159	2	41	44	3	0
PFAST ROTO DROM	PFAST	1,385	147	165	95	197	441	40	95	147	17	41
PFAST AVOSS	PFAST	1,724	453	189	147	142	278	78	48	230	105	55
PFAST DROM AVOSS	PFAST	2,311	523	333	209	202	437	79	87	273	113	55
PFAST AVOSS DROM ROTO	FFAST	3,100	579	360	223	335	736	124	137	389	120	96
AFAST baseline	CT	8,063	1,499	579	463	1,158	995	234	348	1,884	486	418
AFAST DROM	AFAST	554	62	145	56	54	162	1	28	41	6	0
AFAST ROTO DROM	AFAST	1,190	96	173	70	144	430	34	67	126	10	40
AFAST AVOSS	AFAST	1,380	297	178	116	108	247	65	34	203	93	40
AFAST DROM AVOSS	AFAST	1,897	345	325	163	159	401	65	58	243	98	40
AFAST AVOSS DROM ROTO	AFAST	2,541	376	355	179	247	676	104	92	330	102	80
ATM-1 CTAS/3DFMS	AFAST	1,860	285	139	113	248	305	66	63	485	104	50
ATM-1 ROTO DROM	AFAST	2,855	362	310	176	342	707	99	114	543	113	89
ATM-1 DROM AVOSS	AFAST	3,492	567	450	276	364	609	131	100	702	210	83
ATM-1 AVOSS DROM ROTO	AFAST	4,217	615	533	295	428	941	168	140	762	214	121
ATM-2 CTAS/4DFMS	AFAST	4,598	667	372	275	589	728	163	150	1,209	289	155
ATM-2 AVOSS DROM ROTO	AFAST	6,490	888	866	414	693	1,180	249	197	1,404	381	218

The investigation was based on an engineering evaluation of three groups of five current aircraft types (discussed below) operated by major carriers and that could be retrofitted with the TAP displays, both head-up and panel mounted. Further, these aircraft were to continue in service in sufficient numbers so as to be an important segment of U.S. air carrier operations for at least the next 10 years (2000 to 2010) and would be representative of the major types of commercial airline operations.

Examined were the requirements that would be necessary to physically integrate the TAP system and displays into aircraft. Included are estimates of the installation integration tasks that would be involved for the current and future aircraft fleets; existing equipment that must be displaced in order to accommodate the TAP equipment; additional computational resources and data sources that would be required; and software changes and additions that would be necessary.

The first group of aircraft that were examined consisted of five specific aircraft, selected on the basis of high fleet count, that would likely be the most frequent users of air carrier hub airports. These were the Embraer EMB-120 for commuter service; the McDonnell Douglas MD-80 series for medium range regional service; and the Boeing B-737-300, -400, and -500 for longer range regional service. The Embraer EMB-120, the McDonnell Douglas MD-87, and the Boeing B-737-400 were selected for analysis.

The second group of aircraft that were examined included long-range aircraft with full glass cockpits. Considered in the selection was the fact that although these aircraft have a lower frequency of arrival and departure delays at regional hub airports or at major international connecting airports, the adverse cost effects of their delays on any air carrier's overall system can be very high. The aircraft considered in this group

were the Boeing B-747-400, B-757, B-767, B-777, and the MD-11. The Boeing B-747-400 was selected as representative of this group.

The third group included aircraft types defined as "classic" because of their age, primarily Boeing B-747-200s and -300s. Many of these are being converted to cargo/freighters and as such they will incur the high costs associated with late freight deliveries. It is these aircraft that are fitted with the old electro-mechanical primary instruments that present a major retrofit challenge for TAP retrofit technology. The Boeing B-747-200F was chosen for this group.

These aircraft types span a range of cockpit instrumentation from the oldest electro-mechanical instrumentation, commonly referred to as the "classic" cockpit, to the newer Electronic Flight Instrument System (EFIS) with two or more electronic displays in the cockpit, to the newest full-up EFIS glass cockpit having six large multifunction color displays.

The investigation indicated that both HUD and panel-mounted displays could be retrofitted into all five types of aircraft. However, the cost of retrofitting the TAP systems and displays would be very high, of the order of \$400,000 to \$1,000,000 per aircraft. The highest cost would be incurred in retrofitting the long-range classic-type aircraft. The analysis further showed that, despite their newness, retrofitting the glass-cockpit-type aircraft would be the next most expensive. The retrofit approach requiring the least effort appeared to be a separate system as opposed to integration into existing systems. A self-contained TAP Processor Unit with a centrally mounted display should be considered as the basic approach for retrofitting the current aircraft, because minimal change will be required to drive electronics, computers, and software.

Another major consideration affecting the introduction of the TAP technology into commercial aircraft is certification. This includes not only the direct costs for verification (analysis and testing) and validation of new hardware and

software, but also the cost of re-verification of all previously existing hardware and software that could be affected by the addition of the TAP systems and displays, in order to ensure that none of the existing functionality, integrity and availability of the existing hardware/software has been adversely affected. Because of the size of the commercial aircraft fleet and the number of aircraft types affected, certification will be a major and very costly undertaking. For example, cost estimates for recertification of software, especially for glass-cockpit configurations, can range from \$1,000,000 to \$4,000,000 for the first certification and thereafter from about \$800,000 to \$3,000,000 per aircraft of the same type (ref. 15).

The TAP objective of increased throughput and efficiency depends on several factors, of which technical feasibility is only one. Another is the recognition that the different TAP functions and displays (CTAS/FMS, AILS, ROTO, and T-NASA) may not have equal appeal nor be operationally justifiable by all air carriers. In the final analysis, the most powerful influence on airline adoption of the TAP technology is the economic benefits expected to accrue to the air carriers from the TAP.

## Conclusions

Ground and airborne technologies developed in the TAP project were successful in increasing throughput at major airports by safely maintaining good-weather operating capacity during bad-weather conditions. Further, the TAP will increase capacity and reduce delays by reducing spacing requirements between aircraft approaching an airport and by expediting ground operations. The TAP is expected to reduce runway lateral spacing to less than 3,400 ft for independent operations on parallel runways, demonstrate equivalent instrument/clear-weather runway occupancy time, and reduce taxi time. The technical and operational feasibility of these TAP technologies (noted below) are being developed to meet these goals. They were successfully demonstrated during deployment at the DFW ATC Center and TRACON, at the Denver ATC Center, as integrated

systems during flight demonstrations at the Atlanta Hartsfield International Airport and the Minneapolis-St. Paul Airport, and as field tests at DFW.

1. The AVOSS has successfully demonstrated its ability to accurately predict the transport and decay of wake vortices generated by landing aircraft. It will permit safe and significant increases in airport throughput and capacity by determining and validating safe aircraft spacing to prevent wake-turbulence encounters between lead and trailing aircraft in weather conditions ranging from clear to IMC. The AVOSS technologies are applicable to conventional ATC and to CTAS.
2. DROM will provide accurate predictions of arrival ROTs. ROTO, when used in conjunction with and confirmed by DROM, will improve airport capacity throughput by enabling average ROTs of less than 50 sec in severe IMC-2, thus permitting 2.5 n.mi. in-trail separation for all IMC.
3. During flight tests, AILS has demonstrated its ability to safely conduct independent simultaneous approaches with two aircraft in poor weather conditions to parallel runways with centerlines spaced to 2,500 ft apart. This has the potential for providing as much as a twofold increase in throughput for independent IFR approaches to airports with closely spaced parallel runways.
4. T-NASA will help pilots navigate on the airport surface in low visibility conditions and at night by providing a taxi in/out route, thus increasing safety. Its major components are a panel-mounted EMM with route, own-ship, and traffic location; scene-linked route/taxi information virtually projected by a HUD onto the forward scene; and 3-D audio alerts and warnings. T-NASA benefits include improved low-visibility surface navigation, increased surface situational awareness in low-visibility conditions, runway incursion avoidance, and reduced ROT.

5. The CTAS/FMS is conceptually viewed as being near-term and requiring no data-link capability, and in the far-term as using data-link between air and ground. Potential benefits from both levels of CTAS/FMS integration can be quite substantial since it facilitates information exchange between the CTAS and FMS.

In the near term, the CTAS has three main automation decision support tools which have been successfully developed and demonstrated for use by Center and TRACON controllers.

1. The Traffic Management Advisor (TMA) which is a sequence and scheduling tool used to estimate when aircraft should arrive at meter fixes on the TRACON boundary
2. En route Descent Advisor (DA) which is a Center tool designed to provide a conflict-free trajectory for each arriving aircraft which results in the aircraft arriving at the TRACON meter fix at the TMA scheduled time
3. A Final Approach Spacing Tool (FAST) which provides runway assignments and sequence advisories in TRACON airspace, assisting controllers in accurately vectoring aircraft onto the final approach along conflict-free paths by providing turn, speed, and altitude advisories

In the far term, the CTAS/FMS integration makes possible the use of data-link capabilities permitting data and information exchange between the CTAS and FMS in three major application areas:

1. The CTAS/FMS data exchange permits prediction of aircraft trajectories with a high degree of accuracy in real time, thereby allowing reduction of separation buffers, downlinking of aircraft state information, and allowing controllers to control and monitor traffic to tighter tolerances
2. FMS operation in the TRACON provides the ability for ATC to uplink a complete trajectory clearance to the cockpit, thus permitting an

accurate FMS track of the cleared trajectory and further reducing extra separation buffers introduced to account for inaccurate manual tracking

3. Improved ATC system ability to accommodate user-preferred routes for arrivals in the Center transition airspace allowing controllers to handle more traffic without delay, thus significantly decreasing the average time it takes for aircraft to fly the last few hundred miles to a meter fix on the TRACON boundary

The current generation of HUD and panel-mounted TAP displays could be retrofitted into the aircraft that will comprise the air carrier fleet for the next 10 years and will represent the major types of commercial airline operations. Consideration should be given to adoption of generic stand-alone TAP systems as the primary means for retrofitting both the non-glass and glass cockpits.

In the longer term, development of the TAP technology should continue to be vigorously pursued and should include the cost-benefits to the air carriers or the air traffic system of implementing the TAP technology, whether by incorporating it into existing systems or as stand-alone add-on systems.

## Technology Transfer

As mentioned earlier, much of the TAP technology is still at the conceptual stage of development; however, some TAP technology transfer has already occurred. As noted in *Aviation Week & Space Technology* (14 Aug. 2000), Flight Dynamics Inc. (FDI), a wholly owned subsidiary of Rockwell Collins, has incorporated the "scene-linked symbology" HUD taxi display concepts of the T-NASA system into their avionic display suites. They have added guidance cues similar to those of the in-flight HUD symbology as well as runway turn-off cues, both developed by NASA Langley (ROTO). The article further noted that FDI intended to use the T-NASA EMM display practically unchanged. They have termed the combination of these two systems the Surface Guidance System (SGS) which clearly was built on the T-NASA display concept. FDI anticipates that full taxi guidance using the scene-linked symbology would be certified in late 2003 and is planning for data-link route uplinks by 2006.

The joint Ames/Langley simulator demonstration of the full CTAS integrated with FMS discussed earlier indicated that a very efficient arrival flow rate could be achieved in en route transition airspace. The response of the controller and pilot participants to the CTAS/FMS operational concept was enthusiastic. This technology will be transferred to the Distributed Air Ground (DAG) technology element of the AATT project and to the Quiet Aircraft Technology (QAT) and Aviation System Technology Advanced Research (AvSTAR) programs for continued development and refinement.

In fiscal year 1999 the FAA, in its FFP1 program, initiated an approach to implement new technologies for modernization of the National Airspace System. The goal was to move toward free flight operations by deploying systems based on current research prototypes that provided core free-flight capabilities. To this end, the FAA and NASA created a formal technology transfer process that would enhance future technology transfers in terms of cost, time, traceability, and supportability (ref. 22).

## Awards

The AILS Langley and Ames research teams and the Honeywell Technology Center research team were commended for their innovation and contributions toward meeting the NASA Office of Aero-Space Technology (OAT) capacity and safety objectives and were awarded the OAT 2000 "Affordable Air Travel Award." The AILS concept was noted as having demonstrated both technical and procedural safety, and permitted continued operations to closely spaced parallel runways during low-visibility conditions. Research team members were Barry Sullivan, R. Brad Perry, Terence S. Abbott, Dawn M. Elliot, Laura L. Rine, Gary W. Lohr, Marvin C. Waller, and Donner W. Grigsby.

The "Aircraft Vortex Spacing System (AVOSS) Team" was selected as recipients of the prestigious NASA 2001 Turning Goals into Reality (TGIR) Administrator's Award. The AVOSS team was recognized for specific contributions that were valuable and critically important, and advanced the TGIR goals and objectives.





## References

1. Federal Aviation Administration: 1995 Federal Aviation Administration Plan for Research Engineering and Development. DOT/FAA, Washington, D.C, Dec. 1994.
2. Hinton, David A.: An Aircraft Vortex Spacing System (AVOSS) Conceptual Design. NASA TM-110184, August 1995.
3. Hinton, D. A.: An Aircraft Vortex Spacing System (AVOSS) For Dynamical Wake Vortex Spacing Criteria. AGARD 78th Fluid Dynamics Panel Meeting and Symposium on the Characterization and Modification of Wakes from Lifting Vehicles in Fluids, Trondheim, Norway, 20-23 May 1966, AGARD CP-584, Paper 23.
4. Perry, R. Brad; Hinton, David A.; and Stuever, Robert A.: NASA Wake Vortex Research for Aircraft Spacing. AIAA Paper 97-0057, 35th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1997.
5. Hinton, David A.; Charnock, James K.; and Bagwell, Donald R.: Design of an Aircraft Vortex Spacing System for Airport Capacity Improvement. AIAA Paper 2000-0622, 38th Aerospace Sciences Meeting & Exhibit, Reno, Nev., Jan. 2000.
6. Dawn M. Elliott and R. Brad Perry: NASA Research for Instrument Approaches to Closely Spaced Parallel Runways. AIAA Paper 2000-4358, AIAA Guidance, Navigation, and Control Conference, Denver, Colo., Aug. 2000.
7. Williams, D. H.; and Green, S. M.: Flight Evaluation of the Center-TRACON Automation System Trajectory Prediction Process. NASA TP-208439.
8. Lee, Derrick D.; Smith, Alexander; Cassell, Rick; Abdul-Baki, Bassam: NASA Low Visibility and Surface Operations (LVLASO) Runway Occupancy Time (ROT) Analysis. Gateway to the New Millennium; Proceedings of the 18th Digital Avionics Systems Conference (DASC), St. Louis, Mo., Oct 24-29, 1999, vol. 1 (A00-21178 04-01), Piscataway, New Jersey Institute of Electrical and Electronic Engineers, Inc., 1999, p.5.D.5-1 to 5.D.5-9.
9. Hemm, Robert; Shapiro, Gerald; Lee, David; Gribko, Joana; and Glaser, Bonnie: Benefit Estimates of Terminal Area Productivity Program Technologies. NASA CR-208989, Jan. 1999.
10. Young, Steven D.; and Jones, Denise R.: Flight Demonstration of Integrated Airport Surface Movement Technologies. NASA TM-206283, Jan. 1998.
11. Young, Steven D.; and Jones, Denise R.: Flight Testing of an Airport Surface Guidance, Navigation, and Control System. Presented at the Institute of Navigation (ION) National Technical Meeting, Long Beach, Calif., Jan. 1998.
12. Hueschen, Richard M.; Hankins, Walter M.; and Baker, L. Keith: Description and Flight Test of a Rollout and Turnoff Head-up Display Guidance System. 17th Digital Avionics Systems Conference, Seattle, Wash., Oct. 1998.
13. Beskenis, Sharon O.; Green, David F. Jr.; Hyer, Paul V.; and Johnson, Edward J., Jr.: Integrated Display System for Low Visibility Landing and Surface Operations. NASA CR-208446, July, 1998.

14. Johnson, Edward J., Jr.; and Hyer, Paul V.: Roll-Out and Turn-Off Display Software for Integrated Display System. Lockheed Martin Engineering & Sciences Company, Hampton, Va. NASA CR-209731.
15. Hooey, B. L.; Schwirzke, M. L.; McCauley, M. E.; Renfroe, D.; Purcell, K.; and Andre, A. D.: Issues in the Procedural Implementation of Low-Visibility Surface Operations Displays. Proceedings of the 10th International Symposium on Aviation Psychology, Ohio State University, Columbus, Ohio, May, 1999, pp. 797-803.
16. Hooey, B. L.; Schwirzke, M. F. J.; McCauley, M. E.; Purcell, K. P. and Andre, A. D.: Initial Identification of Procedural Issues for the Future Deployment of Terminal Area Productivity (TAP) Technologies. Report MTI 98-940506-36-1, Monterey Technologies Inc., Monterey, Calif., 1998.
17. Cotton, John; Johnson, Walter A.; and Schwirzke, Martin F. J.; and Hennessy, Robert T.: Issues in the Physical Integration of Terminal Area Productivity (TAP) System and Displays into Commercial Aircraft. Report MTI 99-940506-36-2, Monterey Technologies, Inc., Monterey, Calif., 1999.
18. Andre, A. D.; Hooey, B. L.; Foyle, D. C.; and McCann, R. S.: Field Evaluation of T-NASA: Taxi Navigation and Situation Awareness System. Proceedings of the AIAA/IEEE/SAE 17th Digital Avionics System Conference, 1998, pp. 47:1- 47:8.
19. Hooey, B. L.; Foyle, D. C.; and Andre, A. D.: Integration of Cockpit Displays for Surface Operations: The Final Stage of a Human-Centered Design Approach. Proceedings of the AIAA/SAE World Aviation Congress, Paper 2000-01-5521. SAE International, Warrendale, Pa., 2000.
20. McCann, R. S.; Hooey, B. L.; Parke, Bonny; Foyle, D. C.; Andre, A. D.; and Kanki, B.: An Evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) System in High-Fidelity Simulation. Proceedings of the AIAA/SAE 1998 World Aviation Congress, Paper 985541, Sept., 1998.
21. Lee, David A.; Kostiuk, Peter F.; Hemm, Robert V.; Wingrove, Earl R. 111; and Shapiro, Gerald : Estimating the Effects of the Terminal Area Productivity Program. NASA CR-201682. Logistics Management Institute, McLean, Va., April 1997.

## Bibliography

This is a partial bibliography of TAP-related publications. It is presented in two parts: the first part is a chronological list of reports and papers prepared by NASA Centers, other Government agencies, and industry in the period 1977 through 2000: the second part lists publications generated by FMS/Center Automation System and Wake Vortex Program work performed by the Langley Research Center.

### Chronological List

#### Year: 2000

Callantine, T. J.: A Glass Cockpit Crew Activity Analysis Tool. SAE Report 2000-01-5522, 2000.

Haissig, C. M.; Corwin, B.; and Jackson, M.: Designing an Airborne Alerting System for Closely Spaced Parallel Approaches. AIAA Paper 99-3986, AIAA Guidance, Navigation and Control Conference, Portland, Oreg., 2000.

Hinton, David A.; Charnock, James K.; and Bagwell, Donald R.: Design of an Aircraft Vortex Spacing System for Airport Capacity Improvement. AIAA Paper 2000-0622, 38<sup>th</sup> AIAA Aerospace Sciences Meeting & Exhibit, January, 2000, Reno, NV.

Hooey, B. L.; Foyle, D. C.; Andre, A. D.; Purcell, K. P.; and Dowell, S.: Optimizing Airport Surface Operations Using Datalink and the Taxiway-Navigation and Situation Awareness (T-NASA) Display Suite. Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society, Santa Monica, Calif., vol. 3, 2000.

Hooey, B. L., Foyle, D. C. and Andre, A. D.: Integrating Datalink and Cockpit Display Technologies into Current and Future Taxi Operations. Proceedings of the AIAA/IEEE/SAE 19th Digital Avionics System Conference, 2000, p. 100.

Hooey, B. L.; Foyle, D. C.; and Andre, A. D.: Integration of Cockpit Displays for Surface Operations: The Final Stage of a Human-Centered Design Approach. Paper 2000-01-5521, Proceedings of the AIAA/SAE World Aviation Congress, SAE International, Warrendale, Pa., 2000.

Jackson, M. R.; Samanant, P.; and Haissig, C.: Design and Analysis of Airborne Alerting Algorithms for Closely Spaced Parallel Approaches. Paper AIAA 2000-4359, AIAA Guidance, Navigation and Control Conference, Denver, Colo., Aug. 2000.

Prevot, T.; Crane, B.; Palmer, E. A.; and Smith, N.: Efficient Arrival Management Utilizing ATC and Aircraft Automation. HCI-Aero 2000, Toulouse, France, 2000.

Rine, L.; Abbott, T.; Lohr, G.; Elliott, D.; Waller, M. C.; and Perry, R. B.: The Flight Deck Perspective of the NASA Langley AILS Concept. NASA TM 2000-209841, January 2000.

Samanant, Paul; and Jackson, Mike: Description of the AILS Alerting Algorithm. NASA/CR-2000-210109, May 2000.

Waller, M.; Doyle, T.; and McGee, F.: Analysis of the Role of ATC in the AILS Concept. NASA/TM 2000-210091, 2000.

#### Year: 1999

Cheng, V. H. L.; Sharma, V.; and Foyle, D. C.: A Study on Aircraft Taxi Performance Using Nonlinear Feedback Control. Proceedings of the AIAA Guidance, Navigation, and Control Conference, 1999, pp. 1853-1863.

Corker, K. C.; Foyle, D. C.; and Johnson, W. J.: Computational Representation of Human Factors in Advanced Air Traffic Management. Flight Deck International, 19-24, September, U.K. and International Press; Surrey, U.K., Sept. 1999.

- Hemm, R.; and Shappiro, G.: Airborne Information for Lateral Spacing (AILS) Benefit Estimate, NS906S1, 1999.
- Hinton, David A.; Charnock, James K.; Bagwell, Donald R.; and Grigsby, Donner: NASA Aircraft Vortex Spacing System Development Status, AIAA Paper 99-0753, 37th Aerospace Sciences Meeting and Exhibit, Jan. 11-14, 1999, Reno, Nev.
- Hooey, B.; Schwirzke, M.; McCauley, M.; Renfroe, D.; Purcell, K.; and Andre, A. D.: Issues in the Procedural Implementation of Low-Visibility Landing and Surface Operations Displays. Proceedings of the 10th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1999, pp. 797-803.
- Johnson, Edward J., Jr.; and Hyer, Paul V.: Roll-Out and Turn-Off Display Software for Integrated Display System. NASA CR-209731, 1999.
- Lee, Derrick D.; Smith, Alexander; Cassell, Rick; and Abdul-Baki, Bassam: NASA Low Visibility Landing and Surface Operation (LVLASO) Runway Occupancy Time (ROT) Analysis, 1999.
- McCann, R. S., Foyle, D. C., Hooey, B. L., and Andre, A. D. (1999). Pilot interactions with an electronic display suite to support low-visibility taxi. NATO Research and Technology Agency Conference Proceedings, Human Factors & Medicine Panel Third Symposium, 17:1 - 17:13.
- Palmer, E. A.; Williams, D. H.; Prevot, T.; Romahn, S.; Goka, T.; Smith, N.; and Crane, B.: An Operational Concept for Flying FMS Trajectories in Center and TRACON Airspace. Proceedings of the 10th International Symposium on Aviation Psychology, Ohio State Univ., Ohio, May 1990.
- Parke, B.; Kanki, B.; McCann, R. S.; and Hooey, B.: (1999). The Effects of Advanced Navigation Aids on Crew Roles and Communication in Ground Taxi. R. S. Jensen, B. Cox, J. D. Callister, and R. Lavis, eds., Proceedings of the 10th International Symposium on Aviation Psychology, vol. 2, Ohio State Univ., Columbus, Ohio, 1991, pp. 804-809.
- Waller, Marvin C.; and Scanlon, Charles H.: Simulation Study of Instrument Meteorological Condition Approaches to Dual Parallel Runways Spaced 3,400 and 2,500 Feet Apart Using Flight-Deck-Centered Technology. NASA TM-208743, 1999.
- Year: 1998**
- Andre, A. D.; and Cutler, H.: Displaying Uncertainty in Advanced Navigation Systems. Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society, Santa Monica, Calif., pp. 31-35.
- Andre, A. D.: From the Research Lab to the Cockpit: The Development of an Electronic Taxi Map Display. Paper presented at the 3rd Automation Technology and Human Performance Conference, Norfolk, Va., Feb. 1998.
- Andre, A. D.: High Tech Hits the Ground: The Development and Validation of a Taxi Navigation and Situation Awareness (T-NASA) System. Presented at Oshkosh '98, Oshkosh, Wis., July 1998.
- Andre, A. D.; and Hooey, B. L.: The Human Factors of Conducting Field Research: Lessons Learned from the Evaluation of T-NASA. Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society, Santa Monica, Calif., pp. 67-71.
- Andre, A. D.; Hooey, B. L.; Foyle, D. C.; and McCann, R. S.: Field Evaluation of T-NASA: Taxiway Navigation and Situation Awareness System. Proceedings of the AIAA/IEEE/SAE 17th Digital Avionics System Conference, 1998, pp. 47:1-47:8.
- Begault, D. R.: Virtual Acoustics, Aeronautics and Communications. J. Audio Engineering Soc., vol. 46, no. 6, 1998, pp. 520-530.
- Begault, D. R.; Wenzel, E. M.; Tran, L. L.; and Anderson, M. R.: Survey of Commercial Airline Pilot's Hearing Loss. J. Perceptual and Motor Skills, vol. 86, 1998, p. 258.

Doyle, T.; and McGee, F.: Air Traffic and Operational Data for Selected U.S. Airports with Parallel Runways. NASA CR-207675, 1998.

McCann, R. S.; Hooey, B. L.; Parke, B.; Foyle, D. C.; Andre, A. D., and Kanki, B. (1998). An evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) System in High-Fidelity Simulation. Paper 98-5541, Proceedings of the AIAA/SAE World Aviation Congress, SAE International, Warrendale, Pa. 1998.

McCann, R. S.; Hooey, B. L.; Parke, B.; Foyle, D. C.; Andre, A. D. and Kanki, B.: An Evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) System in High-Fidelity Simulation. SAE Transactions: J. Aerospace, vol. 107, 1998, pp. 1612-1625.

Prevot, T.: A Display for Managing the Vertical Flight Path—An Appropriate Task with Inappropriate Feedback. Proceedings of HCI Aero '98, Montreal, Canada, 1998.

RTCA: Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B), Report RTCA/DO-242, Feb. 1998.

Winder, L.; and Kuchar, J. K.: Evaluation of Vertical Collision Avoidance Maneuvers For Parallel Approach. AIAA Paper 98-4242, AIAA Guidance, Navigation and Control Conference, Boston, Mass., August 1998.

Andre, D.: The Design of an Electronic Aircraft Taxi Map Display. Paper presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, April 1997.

Andre, A. D.; Graeber, D. A.; McCann, R. S.; and Foyle, D. C.: Electronic Navigation Display for Aircraft Surface Operations. Paper presented at the 1997 World Aviation Congress, Anaheim, Calif., Oct. 1997.

Callantine, T. J.; Mitchell, C. M.; and Palmer, E. A.: Tracking Operator Activities in Complex Systems: An Experimental Evaluation Using

Boeing 757 Pilots. Proceedings of the International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1997.

Carpenter, B. D.; and Kuchar, J. K.: Probability-Based Collision Alerting Logic for Closely Spaced Parallel Approach. AIAA Paper 97-0222, AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1997.

Carpenter, B. D.; and Kuchar, J. K.: A Probability-Based Alerting Logic for Aircraft on Parallel Approach. NASA CR-201685, April 1997.

Connell, L.: Surface Movement Incidents Reported to the NASA Aviation Safety Reporting System (ASRS). Paper presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, April 1997.

Crane, B.; Palmer, E.; and Smith, N.: Evaluation of a New Descent Procedure for Airline Pilots. Presented at the 9th International Symposium on Aviation Psychology, Columbus, Ohio.

Foyle, D. C.: Taxiway Navigation and Situation Awareness (T-NASA) System. Paper presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, April 1997.

Kuchar, J. K.; and Carpenter, B. D.: Airborne Collision Alerting Logic for Closely Spaced Parallel Approach. Air Traffic Control Quarterly, vol. 5, no. 2, 1997.

McCann, R. S.; Andre, A. D.; Begault, D.; Foyle, D. C.; and Wenzel, E.: Enhancing Taxi Performance Under Low Visibility: Are Moving Maps Enough? Proceedings of the 41st Annual Meeting of the Human Factors and Ergonomic Society, 1997, pp. 37-41.

McCann, R. S.: Advanced Navigation Aids in the Cockpit: Effects on Ground Taxi Performance. Paper presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, April 1997.

Parke, B.: Teamwork in the Terminal Area: Organizational Issues and Solutions. Paper presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1997.

Perry, R. Brad; Hinton, David A.; and Stuever, Robert A.: NASA Wake Vortex Research for Aircraft Spacing. AIAA Paper 97-0057, 35th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan 1997.

Prevot, T.; Palmer, E. A.; and Crane, B.: Flight Crew Support for Automated Negotiation of Descent and Arrival Clearances. Proceedings of the 9th International Aviation Psychology Symposium, Ohio State Univ., Columbus, Ohio, 1997.

Quinn, C.: Ground Taxi Navigation Problems and Training Solutions. Paper presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, April 1997.

Smith, N.; and Palmer, E.: Analysis of Procedure Support Documents and Task Performance. Presented at the 9th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, April 1997.

Van Grent, R. N. H. W.: Free Flight with Airborne Separation Assurance Proceedings of the 10th European Conference. Free Flight, Amsterdam, Netherlands, 1997.

#### **Year: 1996**

Battiste, V.; Downs, M.; and McCann, R. S.: Advanced Taxi Map Display Design for Low-Visibility Operations. Proceedings of the 40th Annual Meeting of the Human Factors And Ergonomics Society, Santa Monica, Calif., 1996, pp. 997-1001.

Battiste, V.; Downs, M.; Sullivan, B. T.; and Soukup, P. A.: Utilization of a Ground Taxi Map to Support Low Visibility Surface Operations. Proceedings of the AIAA Flight Simulation Technologies Conference, San Diego, Calif., 1996.

Begault, D. R.; Wenzel, E. M.; Shrum, R.; and Miller, J.: A Virtual Audio Guidance and Alert System for Commercial Aircraft Operations. Proceedings of International Conference on Auditory Display 96, Palo Alto, Calif., Nov. 1996.

Billings, C. E.: Human-Centered Aviation Automation: Principles and Guidelines. NASA TM-110381, 1996.

Degani, A.: Modeling Human-Machine Systems: On Modes, Error and Patterns of Interaction. Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, Ga., 1996.

Eckhardt, D. E.; Bryant, W. H.; Hueschen, R. M.; and Foyle, D. C.: Low-Visibility Landing and Surface Operations for NASA's Terminal Area Productivity Program. International Civil Aviation Organization (ICAO) All Weather Operations Panel (AWOP) Advanced Surface Movement Guidance and Control Systems (A-SMGCS) Subgroup Meeting, Information Paper 4, Atlanta, Ga., Jan. 1996.

FAA: Benefits of Controller-Pilot Data Link ATC Communications in Terminal Airspace. Final Report DOT/FAA/CT-96/3, Atlantic City, N.J., distributed by National Technical Information Service, Springfield, Va., 1990.

Foyle, D. C.; Andre, A. D.; McCann, R. S.; Wenzel, E.; Begault, D.; and Battiste, V.: Taxiway Navigation and Situation Awareness (T-NASA) System: Problem, Design Philosophy and Description of an Integrated Display Suite for Low-Visibility Airport Surface Operations. SAE Transactions: J. Aerospace, vol. 105, 1996, pp. 1411-1418.

Green, S.; and Vivona, R.: Field Evaluation of Descent Advisor Trajectory Prediction Accuracy. Presented at the AIAA Guidance Navigation and Control Conference, San Diego, Calif., July 1996.

Hinton, D. A.: An Aircraft Vortex Spacing System (AVOSS) For Dynamical Wake Vortex Spacing Criteria. Paper 23, AGARD 78th Fluid Dynamics Panel Meeting and Symposium on the



Characterisation and Modification of Wakes from Lifting Vehicles in Fluids. AGARD CP-584, Trondheim, Norway, May, 1996.

Hutchins, E.: The Integrated Mode Management Interface Final Report. NASA CR-202220, 1996.

Irwin, C. M.; and Walter, K. E.: Low Visibility Surface Operations: Crew Navigation Strategies and Use of Taxi Maps. J. D. Reub and J. D. Garvin, eds. Proceedings of 15th Biennial Applied Behavioral Sciences Symposium, USAFA-TR-96-2, United States Air Force Academy, Colo., 1996, p. 371.

Kocz, Steve: Coordinated Parallel Runway Approaches. NASA CR-201611, 1996.

McCann, R. S.; Foyle, D. C.; Andre, A. D.; and Battiste, V.: Advanced Navigation Aids in the Flight Deck: Effects on Ground Taxi Performance Under Low-Visibility Conditions. SAE Transactions: J. of Aerospace, vol. 105, 1996, pp. 1419-1430.

Mejda, S.; and Andre, A. D.: An Evaluation of Electronic Map Display Features for Aircraft Ground Navigation. Proceedings of the Silicon Valley Ergonomics Conference and Exposition, Silicon Valley Ergonomics Institute, San Jose, Calif., 1996, pp. 43-52.

Prevot, T.; and Onken, R.: In-Flight Evaluation of CASSY: A System Providing Intelligent On-Board Pilot Assistance. Air Traffic Control Quarterly, vol. 3, no. 3, 1996, pp. 183-204.

Tu, D. S.; and Andre, A. D.: Integration of Navigational Information for Aircraft Ground Navigation. Proceedings of the Silicon Valley Ergonomics Conference and Exposition, Silicon Valley Ergonomics Institute, San Jose, Calif., 1996, pp. 218-221.

Vakil, S. S.; Midkiff, A. H.; and Hansmann, R. J.: Development and Evaluation of an Electronic Vertical Situation Display. NASA Grant NAG1-1581, 1996.

Ververs, P. M.; and Wickens, C. D.: The Effect of Clutter and Low-Lighting Symbolology on Pilot Performance with Head-Up Displays. Proceedings of the 40th Annual Meeting of the Human Factors and Ergonomics Society, Santa Monica, Calif., 1996, pp. 62-66.

Waller, M.; and Scanlon, C., Eds: Proceedings of the NASA Workshop on Flight Deck Centered Parallel Runway Approaches in Instrument Meteorological Conditions. NASA CP- 10191, Hampton, Va. 1996.

#### **Year: 1995**

Andre, A. D.: Information Requirements for Low-Visibility Taxi Operations: What Pilots Say. Proceedings of the 8th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1995, pp. 484-488.

Automated Cockpits Special Report I and II. Aviation Week and Space Technology, McGraw Hill Publications, vol. 142, no. 5, Jan. 30, 1995, pp. 52-65; and vol. 142, no. 6, Feb. 6, 1995, pp. 48-57.

Cashion, P.; Feary, M.; Goka, T.; Graham, H.; Palmer, E.; and Smith, N.: Development and Initial Field Evaluation of Flight Deck Procedures for Flying CTAS Descent Clearances. Presented at the 8th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1995.

Foyle, D. C.; McCann, R. S.; and Shelden, S. G.: Attentional Issues with Superimposed Symbolology: Formats for Scene-Linked Displays. Proceedings of the 8th International Symposium on Aviation Psychology, R. S. Jensen and L. A. Rakovan, eds., Ohio State Univ., Columbus, Ohio, 1995, pp. 98-103.

Funk, K.; Lyall, B.; and Riley, V.: A Comprehensive Analysis of Flight Decks with Varying Levels of Automation. Phase 1 Final Report: Perceived Human Factors Problems of Flight Deck Automation. Oregon State Univ., Eugene, Oreg., 1995.



Hinton, David A.: Aircraft Vortex Spacing System (AVOSS) Conceptual Design. NASA TM-110184, 1995.

Lasswell, J. W.; and Wickens, C. D.: The Effects of Display Location and Dimensionality on Taxiway Navigation. Aviation Research Laboratory Technical Report, ARL-95-5, University of Illinois, Urbana, Ill., 1995.

Logsdon, E. W.; Infield, S. E.; Lozito, S.; McGann, A.; Mackintosh, M. A.; and Possolo, A.: Cockpit Data Link Technology and Flight Crew Communication Procedures. Proceedings of the 8th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1995.

McCann, R. S.; and Foyle, D. C.: Scene-Linked Symbolology to Improve Situation Awareness. AGARD Conference Proceedings No. 575, Aerospace Medical Panel Conference on Situation Awareness, 1995, pp. 16:1-16:11.

Palmer, E. A.: Oops, It Didn't Arm. A Case Study of Two Automation Surprises. Proceedings of the 8th International Aviation Psychology Symposium, Ohio State Univ., Columbus, Ohio, 1995.

Pritchett, A.; Carpenter, B. D.; Asari, K.; Kuchar, J. K.; and Hansman, R. J.: Issues in Airborne Systems for Closely-Spaced Parallel Runway Operations. Proceedings of the 14th AIAA/IEEE Digital Avionics Systems Conference, Cambridge, Mass., Nov., 1995.

Sanford, B. D.; Harwood, K.; and Lee, K. K.: Tailoring Advanced Technologies for Air Traffic Control: The Importance of the Development Process. Proceedings of the 8th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1995.

#### **1994**

Dallas-Fort Worth International Airport Short-Term Capacity Enhancement Plan, Sept. 1994.

Erzberger, H.: Concerning the Center-TRACON Automation System (CTAS). Presented to the

Federal Aviation Administration Research and Development Advisory Committee, Washington, D.C., July 12, 1994.

McCann, R. S.; and Foyle, D. C.: Superimposed Symbolology: Attentional Problems and Design Solutions. SAE Transactions, J. Aerospace, vol. 103, 1994, pp. 2009-2016.

#### **Year: 1993**

Lozito, S.; McGann, A.; and Corker, K.: Data Link Air Traffic Control and Flight Deck Environments: Experiment in Flight Crew Performance. Proceedings of the 7th International Symposium on Aviation Psychology, Ohio State Univ., Columbus, Ohio, 1993.

Ebrahimi, Y. S.: Parallel Runway Requirement Analysis Study, Vol. 1, The Analysis. NASA CR-191549, 1993.

Ebrahimi, Y. S.: Parallel Runway Requirement Analysis Study, Vol. 2, Simulation Manual. NASA CR-191549, 1993.

Fadden, D. M.; Braune, R.; and Wiedemann, J.: Spatial Displays As a Means to Increase Pilot Situational Awareness. Pictorial Communication in Virtual and Real Environments, Ellis, Kaiser; and Grunwald, eds., Taylor and Francis, London, 1993, pp. 172-181.

Morrow, D.; and Rodvold, M.: The Influence of ATC Message Length and Timing on Pilot Communication. NASA CR-177621, 1993.

Palmer, E. A.; Hutchins, E.; Ritter, R.; and Van Cleemput, I.: Altitude Deviations: Breakdowns of an Error Tolerant System. NASA TM-108788, 1993.

Sarter, N. B.; and Woods, D. D.: Cognitive Engineering in Aerospace Application: Pilot Interaction with Cockpit Automation. NASA CR-17716, 1993.

**Year: 1992**

Den Braven, W.: Design and Evaluation of an Advanced Air-Ground Data-Link System for Air Traffic Control. NASA TM-103899, 1992.

**Year: 1991**

Federal Aviation Administration: Precision Runway Monitor Demonstration Report. Document DOT/FAA/RD-91/5, Washington, D.C., 1991.

Williams, D. H.; and Green, S. M.: Airborne Four-Dimensional Flight Management in a Time-Based Air Traffic Control Environment. NASA TM-4249, 1991.

**Year: 1989**

Wiener, E. L.: Human Factors of Advanced Technology ("Glass-Cockpit") Transport Aircraft. NASA CR-177528, 1989.

**Year: 1977**

Credeur, Leonard: Basic Analysis of Terminal Operation Benefits Resulting from Reduced Vortex Separation Minima. NASA TM-78624, 1977.

**FMS/Center Automation System**

Gilliland, B.: FMS-CTAS Operational Concepts: FMS Crew Procedure Development. Rev. 2, Task 13 (2.2), Contract NAS1-20219, Mar. 1997.

Burdon, D.: CTAS-FMS Interoperability Issues. Rev. B, Task 6, Contract NAS1-20219, July 1997.

Green, S. M.; Goka, T.; and Williams, D. H.: Enabling User Preferences through Data Exchange. AIAA Paper 97-3682, 1997.

Nguyen, K.: Aeronautical Data Links - Applicability to CTAS-FMS Data Exchange, Task 13 (1.1), Contract NAS1-20219, June 1996.

Nguyen, K.; Heinke, A. M.: CTAS Air-Ground Data Link Applications, Rev. 1, Task 13 (1.2) Contract NAS1-20219, Dec. 1996.

Gilliland, B.: FMS-CTAS Operational Concepts: FMS Arrival Procedure Development, Task 13 (2.1), Contract NAS1-20219, Dec. 1996.

**Wake Vortex Program****Program Description**

Stough, H. P., III; Greene, G. C.; Stewart, E. C.; Stuever, R. A.; Jordan, F. L.; Rivers, R. A.; and Vicroy, D. D.: NASA Wake Vortex Research. AIAA Paper 93-4004, AIAA Aircraft Design, Systems, and Operations Meeting, Monterey, Calif., August 1993.

Vicroy, D.; Bowles, R.; Brandon, J. M.; Greene, G. C.; Jordan, F. L. Jr.; Rivers, R. A.; Stewart, E. C.; Stough, H. P., III; and Stuever, R. A.: NASA Wake Vortex Research. ICAS-94-6.2.2, 19th Congress of the International Council of the Aeronautical Sciences, Anaheim, Calif., September 1994.

Perry, R. Brad; Hinton, David A.; and Stuever, Robert A.: NASA Wake Vortex Research for Aircraft Spacing. AIAA Paper 97-0057, 35th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1997.

Credeur, Leonard; and Perry, R. Brad, eds: Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop. NASA CP-206235, Nov. 1997.

**AVOSS Concept/Design**

Hinton, David A.: Aircraft Vortex Spacing System (AVOSS) Conceptual Design. NASA TM-110184, August 1995.

Hinton, D.A.: An Aircraft Vortex Spacing System (AVOSS) for Dynamical Wake Vortex Spacing Criteria. AGARD CP-584, Paper 23, Proceedings of AGARD 78th Fluid Dynamics Panel Meeting and Symposium on the Characterization and Modification of Wakes from Lifting Vehicles in Fluids, Trondheim, Norway, May 1996.

Dasey, Timothy J.; and Hinton, David A.: Nowcasting Requirements for the Aircraft Vortex

Spacing System (AVOSS). Paper 10.1, 79th Annual Meeting of the American Meteorological Society, Eighth Conference on Aviation, Range, and Aerospace Meteorology, January 1999, Dallas, Tex.

Hinton, David A.; Charnock, James K.; Bagwell, Donald R.; and Grigsby, Donner: NASA Aircraft Vortex Spacing System Development Status. AIAA Paper 99-0753, 37th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Hinton, David A.; Charnock, James K.; and Bagwell, Donald R.: Design of an Aircraft Vortex Spacing System (AVOSS) for Airport Capacity Improvement. AIAA Paper 2000-0622, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Riddick, Stephen E.; and Hinton, David A.: An Initial Study of the Sensitivity of Aircraft Vortex Spacing System (AVOSS) Spacing Sensitivity to Weather and Configuration Input Parameters. NASA TM-209849, January, 2000.

Hinton, David A.; and O'Connor, Cornelius J.: Development of a Wake Vortex Spacing System for Airport Capacity Enhancement and Delay Reduction. Paper 3.E.6, 19th Digital Avionics Systems Conference, Philadelphia, Pa., Oct. 2000.

### **Wake Vortex Modeling & Behavior**

Greene, George C.: An Approximate Model of Vortex Decay in the Atmosphere. AIAA Paper 85-1835-CP, Aug. 1985, See also J. of Aircraft, vol. 23, no. 7, July 1986, pp. 566-573.

Zheng, Z.; and Ash, R. L.: Viscous Effects on a Vortex Wake in Ground Effect. Proceedings of the Federal Aviation Administration International Wake Vortex Symposium, Washington, D.C., Oct. 1991, pp. 31-1 to 31-30.

Zheng, Z.; and Ash, R.L.: Prediction of Turbulent Wake Vortex Motion near the Ground. FED Vol. 151, Transitional and Turbulent Compressible Flows, ASME, 1993.

Zheng, Z.; and Ash, R. L.: Prediction of Turbulent Wake Vortex Motion near the Ground. FED Vol. 151, Transitional and Turbulent Compressible Flows, L. D. Kral and T. A. Zang, eds., ASME Fluids Engineering Conference, Washington, D.C., 1993, pp. 195-207.

Zheng, Z. C.: Influence of Reynolds Number and Atmospheric Effects on Aircraft Wake Vortices Near the Ground. Ph. D. Dissertation, Department of Mechanical Engineering and Mechanics, Old Dominion University, Norfolk, Va., 1993.

Ma, K.; and Zheng, Z.: 3D Visualization of Unsteady 2D Airplane Wake Vortices. Proceedings of the Visualization '94 Conference, IEEE Computer Society Press, Washington, D.C., 1994, pp. 124-131. Also International Council of the Aeronautical Sciences Report No. 94-45.

Ash, R. L.; Zheng, Z. C.; and Greene, G. C.: Cross Wind Effects on Turbulent Aircraft Wake Vortices Near the Ground. AIAA Paper 94-2381, 25th AIAA Fluid Dynamics Conference, Colorado Springs, Colo., June 1994.

Zheng, Z. C.; Ash, R. L.; and Greene, G. C.: A Study of the Influence of Cross Flow on the Behavior of Aircraft Wake Vortices near the Ground. ICAS-94-4.5.3, 19th Congress of the International Council of the Aeronautical Sciences, Anaheim, Calif., Sept. 1994.

Zheng, Z. C.: A Consistent Boundary Condition for Vorticity/Stream-Function Simulations of Wall-Bounded Vortex Flows. Numerical Methods in Laminar and Turbulent Flow, vol. 9, pt. 1., Ed. C. Taylor and P. Durbetaki, eds., Pineridge Press, Swansea, U.K., 1995, pp. 179-190. Proceedings of the 9th International Conference held in Atlanta, Georgia, 1995.

Ash, R. L.; and Zheng, Z. C.: Numerical Simulations of Commercial Aircraft Wakes Subjected to Airport Surface Weather Conditions. AIAA Paper 96-0660, 34th AIAA Aerospace Sciences Meeting and Exhibit, Jan. 1996, Reno, Nev.

Corjon, A.; Zheng, Z. C.; and Greene, G. C.: Model of the Behavior of Aircraft Wake Vortices Experiencing Crosswind Near the Ground. AIAA Paper 96-2516, 27th AIAA Fluid Dynamics Conference, New Orleans, La., June 1996.

Proctor, F. H.: Numerical Simulation of Wake Vortices Measured During the Idaho Falls and Memphis Field Programs. AIAA Paper 96-2496, 14th AIAA Applied Aerodynamics Conference Proceedings pt. 2, New Orleans, La., June 1996, pgs. 943-960.

Zheng, Z. C.: The Effects of Atmospheric Turbulence on Aircraft Wake Vortices Near the Ground. AIAA Paper 96-1954, 27th AIAA Fluid Dynamics Conference, New Orleans, La., June 1996.

Zheng, Z. C.; and Ash, R. L.: A Study of Aircraft Wake Vortex Behavior Near the Ground. AIAA J. vol. 34, no. 3, 1996, pp. 580-589.

Ma, K. L.; and Zheng, Z. C.: Volume Visualization of Airplane Wake Vortices. Flow Visualization VII, Proceedings of the Seventh International Symposium on Flow Visualization, J. P. Crowder, ed., Begell House, Inc., Seattle, Wash., 1996, pgs. 586-591.

Proctor, F. H.; Hinton, D. A.; Han, J.; Schowalter, D. G.; and Lin, Y.-L.: Two Dimensional Wake Vortex Simulations in the Atmosphere: Preliminary Sensitivity Studies. AIAA Paper 97-0056, Presented at the 35th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1997.

Zak, J. Allen; and Rodgers, William G.: Documentation of Atmospheric Conditions During Observed Rising Aircraft Wakes. NASA CR-4767, 1997.

Zheng, Z. C.: Initialization and Simulation of Three-Dimensional Aircraft Wake Vortices. AIAA Paper 97-2264, 15th AIAA Applied Aerodynamics Conference, Atlanta, Ga., June, 1997.

Han, J.; Lin, Y.-L.; Schowalter, D. G.; Arya, S. P.; and Proctor, F. H.: Large-Eddy Simulation of Aircraft Wake Vortices: Atmospheric Turbulence Effects. 12th Symposium on Boundary Layers and

Turbulence, American Meteorological Society, Vancouver, Canada, July-August, 1997, pp. 237-238.

Proctor, Fred H.: The NASA-Langley Wake Vortex Modeling Effort in Support of an Operational Aircraft Spacing System. AIAA Paper 98-0589, 36th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1998.

Sarpkaya, T.: Decay of Wake Vortices of Large Aircraft. AIAA Paper 98-0592, 36th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1998. Also AIAA J., vol. 36, no. 9, pp. 1671-1679.

Robins, Robert E.; Delisi, Donald P.; Greene, George C.: Development and Validation of a Wake Vortex Prediction Algorithm. AIAA Paper 98-0665, 36th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1998.

Zheng, Z. C.; and Baek, K.: Shear-Layer Effects on Trailing Vortices. AIAA Paper 98-0316, 36th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1998.

Ash, R. L., and Zheng, Z. C.: Numerical Simulations of Commercial Aircraft Wakes Subjected to Airport Surface Weather Conditions. J. of Aircraft, vol. 35, no. 1, Jan.-Feb., 1998, pp. 18-26.

Baek, Ki-Hyun: Simulations of Shear Layer Effects and Crow Instability on Aircraft Wake Vortices. Masters Thesis, Department of Mechanical Engineering, University of South Alabama, July, 1998.

Vicroy, Dan D.; Vijgen, Paul M.; Reimer, Heidi M.; Gallegos, Joey L.; and Spalart, Philippe: Recent NASA Wake-Vortex Flight Tests, Flow-Physics Database and Wake-Development Analysis. SAE Paper 985592, 1998 World Aviation Congress and Exhibition, Anaheim, Calif., Sept. 1998.

Proctor, Fred H.; and Han, Jongil: Numerical Study of Wake Vortex Interaction with the Ground Using the Terminal Area Simulation System. AIAA

Paper 99-0754, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Shen, Shaohua; Ding, Feng; Han, Jongil; Lin, Yuh-Lang; Arya, S. Pal; and Proctor, Fred H.: Numerical Modeling Studies of Wake Vortices: Real Case Simulations. AIAA Paper 99-0755, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Han, Jongil; Lin, Yuh-Lang; and Arya, S. Pal: Large Eddy Simulation of Aircraft Wake Vortices in a Homogeneous Atmospheric Turbulence: Vortex Decay and Descent. AIAA Paper 99-0756, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Robins, Robert E.; and Delisi, Donald P.: Further Development of a Wake Vortex Predictor Algorithm and Comparisons to Data. AIAA Paper 99-0757, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Sarpkaya, T.: New Model for Vortex Decay in the Atmosphere. AIAA Paper 99-0761, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999. Also *J. Aircraft*, vol. 37, no. 1, pp. 53-61.

Zheng, Z. C. and Baek, K.: N-S Simulations of Crow-Type Instabilities in Vortex Wake. AIAA Paper 99-0981, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Zak, J. A.; Rodgers, W. G.; and Rivers, R. A.: Observed Rising Aircraft Wakes at Flight Altitudes. Paper 10.2, 8th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Society 79th Annual Meeting, Dallas, Tex., Jan. 1999.

Zheng, Z. C.; and Baek, K.: Inviscid Interactions Between Wake Vortices and Shear Layers. *J. Aircraft*, vol. 36, no. 2, Mar.-April, 1999, pp. 477-480.

Han, J.; Lin, Y-L; Schowalter, D. G.; Arya, S. P.; and Proctor, F. H.: Large Eddy Simulation of Aircraft Wake Vortices within Homogeneous

Turbulence: The Crow Instability. *AIAA J.*, vol. 38, no. 2, Feb. 2000, pp. 292-300.

Han, J.; Lin, Y-L.; Arya, S.P., and Proctor, F. H.: Numerical Study of Wake Vortex Decay and Descent in a Homogeneous Atmospheric Turbulence. *AIAA J.*, vol 38, no. 4, April 2000, pp. 643-656.

Sarpkaya, T.; Robins, R.; and Delisi, D.: Wake-Vortex Eddy Dissipation Model Predictions Compared with Observations. AIAA Paper 2000-0625, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Zheng, Z.; and Lim, S.: Validation and Operation of a Vortex-Wake/Shear Interaction Model. AIAA Paper 2000-0626, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Lin, Yuh-Lang; Han, Jongil; Zhang, Jing; Ding, Feng; Arya, S. Pal; and Proctor, Fred H.: Large Eddy Simulation of Wake Vortices in the Convective Boundary Layer. AIAA Paper 2000-0753, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Switzer, George F.; and Proctor, Fred H.: Numerical Study of Wake Vortex Behavior in Turbulent Domains with Ambient Stratification. AIAA Paper 2000-0755, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Proctor, Fred H.; Hamilton, David W.; and Han, Jongil: Wake Vortex Transport and Decay in Ground Effect: Vortex Linking with the Ground. AIAA Paper 2000-0757, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Proctor, F. H.; and Switzer, G. F.: Numerical Simulation of Aircraft Trailing Vortices. 9th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Society, Orlando, Fla., Sept. 2000, pp. 511-516.

Hamilton, David W.; and Proctor, Fred H.: Wake Vortex Transport in Proximity to the Ground. Paper 3.E.5, 19th Digital Avionics Systems Conference, Philadelphia, Pa., Oct. 2000.



Zheng, Z. C.; and Lim, S. H.: 2000, Validation and Operation of a Wake Vortex/Shear Interaction Model. *J. Aircraft*, vol. 37, no. 6, Nov.-Dec. 2000, pp. 1073-1078.

Proctor, F. H.; Hamilton, D. W.; Han, J.; and Switzer, G. F.: Simulations of Wake Vortex Decay in the Atmosphere. OA-24 (abstract only), 25th General Assembly of the European Geophysical Society, Nice, France 2000.

### **Planetary Boundary Layer Measurement and Modeling**

Schowalter, D. G.; DeCroix, D. S.; Lin, Y-L.; Proctor, F. H.; Arya, S.P.; and Kaplan, M. L.: Turbulent Statistics in the Atmospheric Boundary Layer: A Comparison of Large Eddy Simulation with Observations. 11th Symposium on Boundary Layers and Turbulence, Charlotte, N.C., Mar. 1995.

Schowalter, D. G.; DeCroix, D. S.; Lin, Y-L.; Arya, S. P.; and Kaplan, M. L.: The Sensitivity of Large-Eddy Simulation to Local and Nonlocal Drag Coefficients at the Lower Boundary. NASA CR-198310, 1996.

Schowalter, David G.; DeCroix, David S.; Lin, Yuh-Lang; Arya, S. Pal; and Kaplan, Michael: Planetary Boundary Layer Simulation Using TASS. NASA CR-198325, 1996.

Schowalter, D. S.; Lin, Y.-l.; and Arya, S. P.: The Evening Transition of the Planetary Boundary Layer: A Case Study. 1st International Conference on Nonlinear Problems in Aviation and Aerospace, International Federation of Nonlinear Analysis and International Federation of Information Processing, Daytona Beach, Fla., May 1996.

Matthews, M. P.; Dasey, T. J.; Perras, G. P.; and Campbell, S. D.: Planetary Boundary Layer Measurements for the Understanding of Aircraft Wake Vortex Behavior. Paper 5.5, 7th Conference on Aviation Weather Systems, American Meteorological Society, Long Beach, Calif., Feb. 1997.

DeCroix, David S.; Lin, Yuh-Lang; Schowalter, David G.: Cellular Convection Embedded in the Convective Planetary Boundary Layer Surface Layer. *J. Wind Engineering and Industrial Aerodynamics*, vol. 67-68, April 1997, pp. 387-401.

Kaplan, Michael L.; Weglarz, Ronald P.; Lin, Yuh-Lang; and Shaltanis, Dan: The Predictability of Shallow Terrain-Induced Meso-Scale Jetogenesis within the Nocturnal PBL. 12th Conference on Numerical Weather Prediction, American Meteorological Society, Jan. 1998, pp. 65-68.

Shaltanis, Dan A.: Using the Divergence Equation to Retrieve the Mass Field, the Addition of Wind Profiler Data, and the Application to the Planetary Boundary Layer. Thesis submitted to the Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, N.C., 1998.

Matthews, Michael P.; and Denneno, Andrew P.: Integration of Multiple Meteorological Sensor Observations for Wake Vortex Behavior Comparison. Paper 11.1, 79th Annual Meeting of the American Meteorological Society, 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas, Tex., Jan. 1999.

Kaplan, Michael L.; Weglarz, Ronald P.; Lin, Yuh-Lang; Ensley, Darrell B.; Kehoe, Jennifer K.; and Decroix, David S.: A Terminal Area PBL Prediction System for DFW. AIAA Paper 99-0983, 37th AIAA Aerospace Sciences Meeting Exhibit, Reno, Nev., Jan. 1999.

Charney, Joseph J.; Kaplan, Michael L.; Lin, Yuh-Lang; and Pfeiffer, Karl D.: A New Eddy Dissipation Rate Formulation for the Terminal Area PBL Prediction System (TAPPS). AIAA Paper 2000-0624, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 2000.

Han, Jongil; Arya, S. Pal; Shen, Shaohua; Lin, Yuh-Lang: An Estimation of Turbulent Kinetic Energy and Energy Dissipation Rate Based on Atmospheric Boundary Layer Similarity Theory. NASA CR-210298, 2000.

Kaplan, Michael L.; Lin, Yuh-Lang; Charney, Joseph J.; Pfeiffer, Karl D.; Ensley, Darrell B.; DeCroix, David S.; and Weglarz, Ronald P.: A Terminal Area PBL Prediction System at Dallas-Fort Worth and Its Application in Simulating Diurnal PBL Jets. *Bulletin of the American Meteorological Society*, vol. 81, no. 9, Sept. 2000.

Charney, J. J.; Kaplan, M. L.; Lin, Y-L.; Waight III, K. T.; Pfeiffer, K. D.; Thurman, J. A.; and Hill, C. M.: Wind and Temperature Verification Statistics for the Operational Terminal Area PBL Prediction System at the Dallas-Fort Worth International Airport. Preprints, 9th Conference on Aviation, Range, and Aeronautical Meteorology, American Meteorological Society, Orlando, Fla., Sept. 2000, pp. 381-386.

### **Aircraft/Wake Vortex Encounter Modeling**

Dunham, R. E.; Stuever, R. A.; and Vicroy, D. D.: The Challenges of Simulating Wake Vortex Encounters and Assessing Separation Criteria. AIAA Paper 93-3568, AIAA Atmospheric Flight Mechanics Conference, Monterey, Calif., Aug. 1993.

Stewart, E. C.: A Study of the Interaction Between a Wake Vortex and an Encountering Airplane. AIAA Paper 93-3642, AIAA Atmospheric Flight Mechanics Conference, Monterey, Calif., Aug. 1993.

Rossow, V. J.; Sacco, J. N.; Askins, P. A.; Bisbee, L. S.; and Smith, S. M.: Measurements in 80- by 120-Foot Wind Tunnel of Hazard Posed by Lift-Generated Wakes. AIAA Paper 93-3518, 11th AIAA Applied Aerodynamics Conference, Monterey, Calif., Aug. 1993.

Stuever, R. A.; and Greene, G. C.: An Analysis of Relative Wake-Vortex Hazards for Typical Transport Aircraft. AIAA Paper 94-0810, 32nd Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1994.

Rossow, V. J.: Validation of Vortex-Lattice Method for Loads on Wings in Lift-Generated Wakes. AIAA Paper 94-1839, 12th AIAA Applied Aerody-

namics Conference, Colorado Springs, Colo., June 1994.

Doggett, R. V. Jr.; Riveria, J. A. Jr.; and Stewart, E. C.: Flutter Clearance Flight Tests for an OV-10A Airplane Modified for Wake Vortex Flight Experiments. NASA TM-109168, 1995.

Rossow, V. J.; Fong, R. K.; Wright, M. S.; and Bisbee, L. S.: Vortex Wakes of Two Subsonic Transports as Measured in 80- by 120-Foot Wind Tunnel. AIAA Paper 95-1900, AIAA 13th Applied Aerodynamics Conference, San Diego, Calif., June 1995.

Tatnall, C. R.: A Proposed Methodology for Determining Wake-Vortex Imposed Aircraft Separation Constraints. Master of Science thesis, School of Engineering and Applied Science of George Washington University, Washington, D.C., Aug. 1995.

Stuever, R. A.; Stewart, E. C.; and Rivers, R. A.: Overview of the Preparation and Use of an OV-10 Aircraft for Wake Vortex Hazards Flight Experiments. AIAA Paper 95-3935, 1st AIAA Aircraft Engineering, Technology and Operations Congress, Los Angeles, Calif., Sept. 1995.

Walden, A. B.; van Dam, C. P.; and Brandon, J. M.: Modeling of the Interaction Between a Lifting Wing and a Following Aircraft and Comparison with Experimental Results. AIAA Paper 96-0771, 34th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., 1996.

Reimer, H. M.; and Vicroy, D. D.: A Preliminary Study of a Wake Vortex Encounter Hazard Boundary for a B-737 Airplane. NASA TM-110223, 1996.

Fuhrmann, Henri C.: An Evaluation of the Measurement Requirements for an In-Situ Wake Vortex Detection System. NASA TM-110218, 1996.

Rossow, V. J.: Wake-Vortex Separation Distances when Flight-Path Corridors are Constrained. AIAA Paper 96-2500, 14th AIAA Applied Aerodynamics Conference, New Orleans, La., June 1996.



Victroy, D. D.; and Nguyen, T.: A Numerical Simulation Study to Develop an Acceptable Wake Encounter Boundary for a B-737-100 Airplane. AIAA Paper 96-3372, AIAA Atmospheric Flight Mechanics Conference, San Diego, Calif., July 1996.

Victroy, D.; Brandon, J.; Greene, G.; Rivers, R.; Shah, G.; Stewart, E.; and Stuever, R.: Characterizing the Hazard of a Wake Vortex Encounter. AIAA Paper 97-0055, 35th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1997.

Ash, Robert; and Pfouts, Robert A.: A Comparison Between Simulated and Measured Free-Flight Vortex Encounter Behavior in the NASA Langley Full-Scale Wind Tunnel. ODURF No. 198087, Old Dominion University, Norfolk, Va., June 1997.

Hinton, David A. and Tatnall, Chris R.: A Candidate Wake Vortex Strength Definition for Application to the NASA Aircraft Vortex Spacing System (AVOSS). NASA TM-110343, 1997.

Brandon, Jay M.; Jordan, Frank L., Jr.; Buttrill, Catherine W.; Stuever, Robert A.: Application of Wind Tunnel Free-Flight Technique for Wake Vortex Encounters. NASA TP-3672, 1997.

Tatnall, Christopher Rhoads: An Investigation of Candidate Sensor-Observable Wake Vortex Strength Parameters for the NASA Aircraft Vortex Spacing System (AVOSS). NASA CR 206933, 1998.

Stewart, Eric C.: A Piloted Simulation Study of Wake Turbulence on Final Approach. AIAA Atmospheric Flight Mechanics Conference and Exhibit. AIAA Paper-98-4339, Aug. 1998.

### **Wake Vortex Sensors**

Huffaker, R. M.; and Hannon, S. M.: Airport Surveillance Using a Solid-State Coherent Lidar. Fifth and Final Airborne Windshear Detection and Warning Systems Combined Manufacturers' and Technologists' Conference, Pt 2, July 1994, pp. 499-523.

Hannon, S. M.; and Thomson, J. A.: Wake Vortex Detection at Denver Stapleton Airport with a Pulsed 2-micron Coherent Lidar. Fifth and Final Airborne Windshear Detection and Warning Systems Combined Manufacturer's and Technologists' Conference, Pt 2, July 1994, pp. 625-650.

Hannon, S. M.; and Thomson, J. A.: Aircraft Wake Vortex Detection and Measurement With Pulsed Solid-State Coherent Laser Radar. J. Modern Optics, Nov. 1994, p. 2175.

Koch, G. J.; Staton, L. D.; and Nguyen, C.: Design Considerations for an Operational Wake Vortex Lidar Sensor, 8th Conference on Coherent Laser Radar, Keystone, Colo., June 1995.

Dasey, T. J.; and Heinrichs, R.: An Algorithm for the Recognition and Tracking of Aircraft Wake Vortices with a Continuous Wave Coherent Laser Radar. Optical Society of America Topical Meeting on Coherent Laser Radar, Keystone, Colo., July 1995.

Heinrichs, R. M.; Freehart, R. E.; Dasey, T. J.; and Mandra, R. S.: Development and Performance of a CW Coherent Laser Radar for Detecting Wake Vortices. Presented at the Optical Society of America Topical Meeting on Coherent Laser Radar, Keystone, Colo., July 1995.

Marshall, Robert E.; and Myers, Theodore J.: Wingtip Generated Wake Vortices as Radar Targets. IEEE 1996 National Radar Conference, Ann Arbor, Mich., May 1996.

Switzer, George F.: Validation Tests of TASS for Application to 3-D Vortex Simulations. NASA CR-4756, 1996.

Heinrichs, Richard M.; and Dasey, Timothy J.: Analysis of Circulation Data from a Wake Vortex Lidar. AIAA Paper 97-0059, 35th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1997.

Heinrichs, R. M.; Dasey, T. J.; Matthews, M. P.; Campbell, S. D.; Freehart, R. E.; and Perras, G. P.: Measurements of Aircraft Wake Vortices at Mem-

phis International Airport with a CW CO<sub>2</sub> Coherent Laser Radar. SPIE-2737-20, SPIE Symposium on Aerospace/Defense Sensing and Controls, Air Traffic Control Technologies II session, Orlando, Fla., April 1996. Also Proc. Intl. Soc. for Optical Eng. (SPIE), vol. 2737, 1996, pp. 122-133.

Barker, B. C.; Brockman, P.; and Koch, G. J.: Laser Radar Watches the Friendly Skies. Photonics Spectra, Laurin Publications, April 1997, pp. 94-98.

Britt, Charles L.: Estimation of Aircraft Wake Vortex Size and Strength from Coherent Pulsed Lidar Measurements. 9th Conference on Coherent Laser Radar, Linkoping, Sweden, June 1997.

Koch, G. J.; Barker, B. C.; and Britt, C. L.: Development of an Operational Wake Vortex Sensor Based on Pulsed Coherent Lidar. 9th Conference on Coherent Laser Radar, Linkoping, Sweden, June 1997.

Mackenzie, A. I.: Measured Changes in C-Band Radar Reflectivity of Clear Air Caused by Aircraft Wake Vortices. NASA TP-3671, 1997.

Marshall, Robert E.; Mudukutore, Ashok; and Wissel, Vicki L. H.: Radar Reflectivity in Wingtip-Generated Wake Vortices. NASA CR-206259, 1997.

Barker, B. C., Jr.; Koch, G. J.; and Nguyen, D. C.: An Operational Wake Vortex Sensor Using Pulsed Coherent Lidar. 19th International Laser Radar Conference, Annapolis, Md., July 1998.

Britt, Charles L.; Nguyen, Dung Phu Chi; and Koch, Grady: Pulsed Lidar Measurements of Aircraft Wake Vortices at DFW and JFK. AIAA Paper 99-0982, 37th AIAA Aerospace Sciences Meeting and Exhibit, 1999, Reno, Nev., Jan. 1990.

Brockman, P.; Barker, B. C.; Koch, G. J.; Nguyen, D. P. C.; Britt, C. L.; and Petros, M.: Coherent Pulsed Lidar Sensing of Wake Vortex Position and Strength, Winds and Turbulence in the Terminal Area. 10th Conference on Coherent Laser Radar, Mt. Hood, Oreg., June 1999.

## Field Studies

Campbell, S. D.; Dasey, T.; Heinrichs, R.; and Matthews, M. P.: Overview of 1994 Memphis Wake Vortex Testing Program. 6th Conference on Aviation Weather Systems, American Meteorological Society, Dallas, Tex., Jan. 1995.

Campbell, S.; Dasey, T.; Freehart, R.; Heinrichs, R.; Matthews, M.; and Perras, G.: Wake Vortex Field Measurement Program at Memphis, Tenn. AIAA Paper 96-0399, Presented at the 34th Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1996.

Campbell, S. D.; Dasey, T. J.; Freehart, R. E.; Heinrichs, R. M.; Matthews, M. P.; Perras, G. H.; and Rowe, G. S.: Wake Vortex Field Measurement Program at Memphis, Tenn. Data Guide, Project Report NASA/L-2, MIT Lincoln Laboratory, Lexington, Mass., Jan. 14, 1997. Also NASA CR-201690, April 1997.

Dasey, T. J., Campbell, S. D., Heinrichs, R. M., Matthews, M. P., Freehart, R. E., Perras, G. P., and Salamitou, P.: A Comprehensive System for Measuring Wake Vortex Behavior and Related Atmospheric Conditions at Memphis, Tennessee. Air Traffic Control Quarterly, vol. 5, no. 1, 1997, pp. 49-68.

Dasey, T. J.; Cole, R. E.; Heinrichs, R. M.; Matthews, M. P.; Perras, G. P.: Aircraft Vortex Spacing System (AVOSS) Initial 1997 System Deployment at Dallas/Ft. Worth (DFW) Airport. Project Report NASA/L-3, MIT Lincoln Laboratory, Lexington, Mass., July 8, 1998.

Joseph, R. M.; Dasey, T. J.; and Heinrichs, R. M.: Vortex and Meteorological Measurements at Dallas/Ft. Worth Airport. AIAA Paper 99-0760, 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev., Jan. 1999.

Perras, G. H.; and Dasey, T. J.: Turbulence Climatology at Dallas/Ft. Worth (DFW) Airport—Implications for a Departure Wake Vortex Spacing System. Project Report NASA/L-4, MIT Lincoln Laboratory, Lexington, Mass., Nov. 30, 2000.

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<b>13. ABSTRACT (Maximum 200 words)</b> Ground and airborne technologies were developed in the Terminal Area Productivity (TAP) project for increasing throughput at major airports by safely maintaining good-weather operating capacity during bad weather. Methods were demonstrated for accurately predicting vortices to prevent wake-turbulence encounters and to reduce in-trail separation requirements for aircraft approaching the same runway for landing. Technology was demonstrated that safely enabled independent simultaneous approaches in poor weather conditions to parallel runways spaced less than 3,400 ft apart. Guidance, control, and situation-awareness systems were developed to reduce congestion in airport surface operations resulting from the increased throughput, particularly during night and instrument meteorological conditions (IMC). These systems decreased runway occupancy time by safely and smoothly decelerating the aircraft, increasing taxi speed, and safely steering the aircraft off the runway. Simulations were performed in which optimal trajectories were determined by air traffic control (ATC) and communicated to flight crews by means of Center TRACON Automation System/Flight Management System (CTAS/FMS) automation to reduce flight delays, increase throughput, and ensure flight safety.				
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